COMESA 303-4 (2007) (English): Power transformers Part 8: Application guide

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COMESA HARMONISED STANDARD

COMESA/FDHS 303-4:2007

Power transformers — Part 4: Guide to the lightning impulse and switching impulse testing — Power transformers and reactors

REFERENCE: FDHS 303-4:2007

Foreword

The Common Market for Eastern and Southern Africa (COMESA) was established in 1994 as a regional economic grouping consisting of 20 member states after signing the co-operation Treaty. In Chapter 15 of the COMESA Treaty, Member States agreed to co-operate on matters of standardisation and Quality assurance with the aim of facilitating the faster movement of goods and services within the region so as to enhance expansion of intra-COMESA trade and industrial expansion.

Co-operation in standardisation is expected to result into having uniformly harmonised standards. Harmonisation of standards within the region is expected to reduce Technical Barriers to Trade that are normally encountered when goods and services are exchanged between COMESA Member States due to differences in technical requirements. Harmonized COMESA Standards are also expected to result into benefits such as greater industrial productivity and competitiveness, increased agricultural production and food security, a more rational exploitation of natural resources among others.

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COMESA Standards are subject to review, to keep pace with technological advances. Users of the COMESA Harmonized Standards are therefore expected to ensure that they always have the latest version of the standards they are implementing.

This COMESA standard is technically identical to IEC 60076-4:2002, *Power transformers — Part 4: Guide to the lightning impulse and switching impulse testing — Power transformers and reactors*

INTERNATIONAL STANDARD

IEC 60076-4

First edition
2002-06

Power transformers –

Part 4:
Guide to the lightning impulse and switching impulse testing –
Power transformers and reactors

*This **English-language** version is derived from the original **bilingual** publication by leaving out all French-language pages. Missing page numbers correspond to the French-language pages.*

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Publication numbering

As from 1 January 1997 all IEC publications are issued with a designation in the 60000 series. For example, IEC 34-1 is now referred to as IEC 60034-1.

Consolidated editions

The IEC is now publishing consolidated versions of its publications. For example, edition numbers 1.0, 1.1 and 1.2 refer, respectively, to the base publication, the base publication incorporating amendment 1 and the base publication incorporating amendments 1 and 2.

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Part 4:
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International Electrotechnical Commission, 3, rue de Varembé, PO Box 131, CH-1211 Geneva 20, Switzerland
Telephone: +41 22 919 02 11 Telefax: +41 22 919 03 00 E-mail: inmail@iec.ch Web: www.iec.ch

Commission Electrotechnique Internationale
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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6) Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. The IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 60076-4 has been prepared by IEC technical committee 14: Power transformers.

This International Standard cancels and replaces IEC 60722 published in 1982 and constitutes a technical revision of that document.

The text of this standard is based on the following documents:

FDIS	Report on voting
14/413/FDIS	14/446/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

Annexes A and B are for information only.

IEC 60076 consists of the following parts, under the general title *Power transformers:*

Part 1: General

Part 2: Temperature rise

Part 3: Insulation levels, dielectric tests and external clearances in air

Part 4: Guide to lightning impulse and switching impulse testing – Power transformers and reactors

Part 5: Ability to withstand short-circuit

Part 8: Application guide

Part 10: Determination of sound levels

The committee has decided that the contents of this publication will remain unchanged until 2007. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

POWER TRANSFORMERS –

Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors

1 Scope

This part of IEC 60076 gives guidance and explanatory comments on the existing procedures for lightning and switching impulse testing of power transformers to supplement the requirements of IEC 60076-3. It is also generally applicable to the testing of reactors (see IEC 60289), modifications to power transformer procedures being indicated where required.

Information is given on waveshapes, test circuits including test connections, earthing practices, failure detection methods, test procedures, measuring techniques and interpretation of results.

Where applicable, the test techniques are as recommended in IEC 60060-1 and IEC 60060-2.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60060-1, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60060-2, *High-voltage test techniques – Part 2: Measuring systems*

IEC 60076-3, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60289, *Reactors*

IEC 61083-1, *Instruments and software used for measurement in high-voltage impulse tests – Part 1: Requirements for instruments*

IEC 61083-2, *Digital recorders for measurements in high-voltage impulse tests – Part 2: Evaluation of software used for the determination of the parameters of impulse waveforms*

3 General

This standard is primarily based on the use of conventional impulse generators for both lightning and switching impulse testing of transformers and reactors. The practice of switching impulse generation with discharge of a separate capacitor into an intermediate or low-voltage winding is also applicable. However, the method which employs an additional inductance in series with the capacitor to provide slightly damped oscillations transferred into the high-voltage winding is not applicable.

Alternative means of switching impulse generation or simulation such as d.c. current interruption on an intermediate or low-voltage winding or the application of a part-period of power frequency voltage are not discussed since these methods are not as generally applicable.

Different considerations in the choice of test circuits (terminal connections) for lightning and switching impulse tests apply for transformers and reactors. On transformers, all terminals and windings can be lightning impulse tested to specific and independent levels. In switching impulse testing, however, because of the magnetically transferred voltage, a specified test level may only be obtained on one winding (see IEC 60076-3).

Whilst, on reactors, lightning impulse testing is similar to that on transformers, i.e., all terminals can be tested separately, different considerations apply and different problems arise in switching impulse testing. Hence, in this standard, lightning impulse testing is covered by a common text for both transformers and reactors whilst switching impulse testing is dealt with separately for the two types of equipment.

4 Specified waveshapes

The voltage waveshapes to be used normally during lightning and switching impulse testing of transformers and reactors are given in IEC 60076-3 and the methods for their determination are given in IEC 60060-1.

5 Test circuit

The physical arrangement of test equipment, test object and measuring circuits can be divided into three major circuits:

– the main circuit including the impulse generator, additional waveshaping components and the test object;
– the voltage measuring circuit;
– the chopping circuit where applicable.

This basic arrangement is shown in figure 1.

The following parameters influence the impulse waveshape;

a) the effective capacitance C_t, and inductance of the test object, L_t; C_t is constant for any given design and any given waveshape, L_t is also a constant for any given design. The effective L_t, however, may be influenced by the terminal treatment. It varies between the leakage inductance L_s for short-circuited terminals and L_o for open-circuited terminals. More details in this respect are given in 7.1 and 7.3 and in annex A;
b) the generator capacitance C_g;
c) waveshaping components, both internal and external to the generator, R_{si}, R_{se}, R_p, C_L (plus, where applicable, the impedance of a voltage divider Z_1);
d) the stray inductance and capacitance of the generator and the complete test circuit;
e) chopping equipment, where applicable.

The front time T_1 is determined mainly by combination of the effective surge capacitance of the test object, including C_L, and the generator internal and external series resistances.

The time to half-value T_2 is, for lightning impulses, primarily determined by the generator capacitance, the inductance of the test object and the generator discharge resistance or any other parallel resistance. However, there are cases, for example, windings of extremely low inductance, where the series resistance will have a significant effect also on the wavetail. For switching impulses, other parameters apply; these are dealt with in clause 8.

The test equipment used in lightning and switching impulse applications is basically the same. Differences are in details only, such as values of resistors and capacitors (and the terminal connections of the test object).

To meet the different requirements of the waveshape for lightning and switching impulses, due consideration has to be given to the selection of the impulse generator parameters, such as capacitance and series and discharge (parallel) resistances. For switching impulses, large values of series resistors and/or load capacitors may be necessary, which will result in significant reduction of the efficiency.

While the output voltage of the impulse generator is determined by the test levels of the windings with respect to their highest voltage for equipment U_m for the test object, the required energy storage capability is essentially dependent on the inherent impedances of the test object.

A brief explanation of the principles of waveshape control is given in annex A.

The arrangement of the test plant, test object and the interconnecting cables, earthing strips, and other equipment is limited by the space in the test room and, particularly, the proximity effect of any structures. During impulse testing, zero potential cannot be assumed throughout the earthing systems due to the high values and rates of change of impulse currents and voltages and the finite impedances involved. Therefore, the selection of a proper reference earth is important.

The current return path between the test object and the impulse generator should be of low impedance. It is good practice to firmly connect this current return path to the general earth system of the test room, preferably close to the test object. This point of connection should be used as reference earth and to attain good earthing of the test object it should be connected to the reference earth by one or several conductors of low impedance (see IEC 60060-2).

The voltage measuring circuit, which is a separate loop of the test object carrying only the measuring current and not any major portion of the impulse current flowing through the windings under test, should also be effectively connected to the same reference earth.

In switching impulse testing, since the rates of change of the impulse voltages and currents are much reduced compared with those in a lightning impulse test and no chopping circuit is involved, the problems of potential gradients around the test circuit and with respect to the reference earth are less critical. Nevertheless, it is suggested that, as a precaution, the same earthing practices should be followed as used for lightning impulse testing.

6 Calibration

It is not the intention of this standard to give any recommendation on measuring systems or their calibration but, of course, the apparatus which is used should be approved in accordance with IEC 60060. Before a test, an overall check of the test circuit and the measuring system may be performed at a voltage lower than the reduced voltage level. In this check, voltage may be determined by means of a sphere gap or by comparative measurement with another approved device. When using a sphere gap, it should be recognized that this is only a check and does not replace the periodically performed calibration of the approved measuring system. After any check has been made, it is essential that neither the measuring nor the test circuit is altered except for the removal of any devices for checking.

Information on types of voltage dividers, their applications, accuracy, calibration and checking is given in IEC 60060-2.

7 Lightning impulse tests

7.1 Waveshapes

The values of waveshape specified may not always be obtainable. In the impulse testing of large power transformers and reactors, of low winding inductance and/or high surge capacitance, wider tolerances may have to be accepted.

The surge capacitance of the transformer under test being constant, the series resistance may have to be reduced in an attempt to obtain the correct front time T_1 or rate of rise, but the reduction should not be to the extent that oscillations on the crest of the voltage wave become excessive. If it is considered desirable to have a short front time (preferably within the specified limits) then oscillations and/or overshoots greater than ±5 % of the peak voltage, allowed in IEC 60060-1, may have to be accepted. In such an event, a compromise between the extent of allowable oscillations and the obtainable front time is necessary. In general, oscillations not greater than ±10 % should be aimed at, even with extensions to the front time as necessary and as agreed between manufacturer and purchaser. The value of the test voltage is determined according to the principles of IEC 60060-1.

For large power transformers and particularly the intermediate and low-voltage windings thereof, the virtual time to half-value T_2 may not be achievable within the value set by the tolerance. The inductance of such windings may be so low that the resulting waveshape is oscillatory. This problem may be solved to some extent by the use of large capacitance within the generator, by parallel stage operation, by adjustment of the series resistor or by specific test connections of the terminals of windings not under test or, in addition, of the non-tested terminals of windings under test.

Impedance earthing, rather than direct earthing, of the non-tested winding terminals results in a significant increase in the effective inductance. For directly earthed terminals, only the leakage inductance (determined by the short-circuit impedance) is involved. For impedance earthed terminals, the main inductance becomes predominant. This can make the effective inductance 100 to 200 times greater than with direct earthing.

When impedance earthing of any non-tested terminal is employed, it is necessary to ensure that the voltage to earth appearing on any non-tested terminal does not exceed

– 75 % of the rated lightning withstand voltage of that terminal for star-connected windings;
– 50 % of the rated lightning withstand voltage of that terminal for delta-connected windings (because of opposite polarity voltages to earth on the delta terminals – see also 7.4).

When the waveshape is oscillatory due to extremely low inductance and/or small impulse generator capacitance, the amplitude of the opposite polarity should not exceed 50 % of the peak value of the first amplitude. With this limitation, guidance for selecting impulse generator capacitance and adjusting waveshapes is given in annex A.

7.2 Impulses chopped on the tail

7.2.1 Time to chopping

Different times to chopping T_c (as defined in IEC 60060-2), will result in different stresses (voltage and duration) in different parts of the winding(s) depending on the winding construction and arrangement employed. Hence, it is not possible to state a time to chopping which is the most onerous either in general or for any particular transformer or reactor. The time to chopping is therefore not regarded as a test parameter provided that it is within the limits of 2 µs and 6 µs as required by IEC 60076-3.

Oscillograms or digital recordings of chopped waves, however, are only comparable for almost identical times to chopping.

7.2.2 Rate of collapse and amplitude of reversed polarity of the chopped impulse

The characteristic events during chopping are largely dependent on the geometrical arrangement of the chopping circuit involved and on the impedance of the chopping circuit and of the test object, all of which determine both the rate of collapse and the amplitude of the opposite polarity peak.

In IEC 60076-3, the amount of overswing to opposite polarity has been limited to 30 % of the amplitude of the chopped impulse. This, in fact, represents a guideline for the arrangement of the chopping circuit and may entail the introduction of additional impedance Z_c in this circuit to meet the limit (see figure 1).

The chopping loop, however, should be as small as possible to obtain the highest rate of collapse, but the overswing to opposite polarity should be limited to less than, or equal to 30 %. On multiple layer windings, the layer impedance may damp the collapse normally to the extent that it does not oscillate around zero (see figure B.20).

The recommendation in IEC 60076-3 to use a triggered-type chopping gap is made because of its advantage in obtaining consistency of the time to chopping, thereby facilitating the comparison of oscillographic or digital recordings not only before but also after chopping. The latter part will only be comparable for reasonably identical times to chopping.

7.3 Terminal connections and applicable methods of failure detection

7.3.1 Terminal connections

It is essential that the terminal connections of the test object and the earthing practices employed relate to the method of failure detection adopted.

Connections for impulse testing are detailed in IEC 60076-3 for transformers and in IEC 60289 for reactors. Normally the non-tested terminals of the phase winding under test are earthed and the non-tested phase windings are shorted and earthed. However, in order to improve the wavetail T_2, resistance earthing of the non-tested windings may be advantageous (see clause 5 and 7.1) and, in addition, the non-tested line terminals of the winding under test may also be resistance earthed.

In addition to the methods of waveshape adjustment in 7.1, the following factors have to be considered:

a) if a terminal has been specified to be directly earthed or connected to a low-impedance cable in service, then that terminal should be directly earthed during the test or earthed through a resistor with an ohmic value not in excess of the surge impedance of the cable;
b) earthing through a low-impedance shunt for the purpose of impulse response current measurements may be considered the equivalent of direct earthing.

When non-linear elements or surge diverters – built into the transformer or external – are installed for the limitation of transferred overvoltage transients, the impulse test procedure should be discussed in advance for each particular case. Refer also to IEC 60076-3.

7.3.2 Applicable methods of failure detection

Failure detection is normally accomplished by examination of the oscillographic or raw data digital records of the applied test voltage and the impulse response current.

Different transients can be recorded and used separately or in combination, as shown in figure 2. These are listed a) to e) below. It is essential, in acceptance testing, to record at least one of these transients in addition to the applied test voltage:

a) the neutral current (for star and zigzag connected windings of which the neutral may be earthed during the test);

b) the winding current (for all other windings and star and zigzag connected windings of which the neutral may not be earthed during the test);

c) the current transferred to an adjacent shorted and non-tested winding, sometimes referred to as capacitively transferred current;

d) the tank current;

e) the voltage transferred to a non-tested winding.

The sum of items a), c) and d) or of items b), c) and d), is sometimes referred to as line current.

When testing reactors, both of the shunt and series types, items c) and e) are inapplicable; item d) may be applied but only as an additional means of transient recording since it is likely to be less sensitive than when used in transformer testing.

7.4 Test procedures

The relevant test sequences for full-wave tests or for full- and chopped-wave tests are given in IEC 60076-3.

The preferred method of test is that of direct application although in special cases where the intermediate or low-voltage winding cannot, in service, be subjected to lightning overvoltages from the system connected to it, the "transferred surge" method may alternatively be employed. The impulse test of the low-voltage winding is then carried out simultaneously with the test of the associated high-voltage winding. In these conditions, the waveform of the transferred voltage does not conform with that specified in IEC 60076-3. It is more important to try to obtain the required voltage level by means of termination resistors of sufficiently high value. However, this may not always be possible even with the highest values of resistors. In this test, high inter-phase voltages may occur on delta-connected windings and the danger of overstressing inter-phase insulation, internal or external, may limit the voltage that can be applied to the low-voltage winding. The appropriate limits may be established by transient analysis with a low-voltage recurrent surge generator.

By their very nature, non-linear protection devices connected across the windings may cause differences between the reduced full-wave and the full-wave impulse oscillograms or digital recordings. Proof that these differences are indeed caused by operation of these devices should be demonstrated by making two or more reduced full-wave impulse tests at different voltage levels to show the trend in their operation. To show the reversibility of any non-linear effects, the same reduced full-wave impulses should follow up the full-wave test voltage in a reversed way.

Example: 60 %, 80 %, 100 %, 80 %, 60 %.

Test methods for transformer neutrals are given in IEC 60076-3. When the indirect method is used, i.e. by an impulse transmitted to the neutral from one or more line terminals, the waveshape cannot be specified since it is controlled basically by the transformer parameters. The direct method, involving an impulse voltage applied to the neutral with all line terminals earthed, permits a longer duration of wavefront, up to 13 µs. In this case, the inductive loading of the generator is significantly increased and it may be difficult to achieve times to half-value set by the tolerances. Impedance earthing of the non-tested terminals of the winding under test may then be applied.

7.5 Recording of tests

7.5.1 General

Either analogue or digital recording systems may be used for the recording of lightning impulse voltage and current response waveshapes.

7.5.2 Analogue and digital recording systems

The requirements for analogue oscilloscopes and digital recorders are given in IEC 61083-1.

Digital recording offers the potential for mathematical interpretation of the results and allows additional mathematical processing to be used, for example, for fault analysis in recordings. These techniques show promise but interpretation of the results is not yet proven nor unambiguous.

It should be emphasized that for the purpose of presenting results for acceptance by comparison of traces, the waveforms obtained by digital measurements should be produced from the raw data and not subjected to any mathematical processing, filtering, smoothing, etc.

It is equally important to use the raw data for non-standard waveshape evaluation.

(Figures B.18, B.19 and B.21 show significant differences in amplitude and front time T_1 and time to half value T_2 evaluations.)

When digital recorders are used as straight-forward measuring instruments for recording of voltage and current waveshapes, without the purpose of mathematical processing (see clause 10) of the recorded data, they are to be regarded as technically advanced analogue instruments.

IEC 60076-3 requires simultaneously the measurement of

a) the applied voltage;

b) at least one of the transients listed in 7.3.2;

hence, at least two independent recording channels are necessary.

While the applied voltage is uniquely defined, the choice of the other characteristic to be recorded is dependent on the selection of the method of failure detection.

7.5.3 Analogue recording of waveshapes

To facilitate the assessment of the test results, which is primarily based on the comparison of recordings taken at reduced and full levels, it is advantageous to provide for recordings of equal amplitude by the use of appropriate attenuators at the oscilloscopes.

7.5.3.1 Analogue recording of the impulse voltage waveshape

a) Determination of the impulse voltage waveshape

The preferred sweep time for records taken for waveshape determination during preliminary adjustment of the test circuit parameters is ≤10 μs for the wavefront record (longer sweep times may be necessary when testing transformer neutrals). The wavetail record should permit the evaluation of the time to half-value and, on occasions, the amplitude of reversed polarity.

b) Applied impulse test voltage wave recording

In order to determine the amplitude of the test wave and to permit detection of any fault which may be present:

– for full waves, the sweep time should not be less than 100 μs;

– for chopped waves, a sweep time of 10 μs to 25 μs is usually found sufficient.

For the test report (see clause 11) one pertinent recording is normally sufficient for acceptance tests; for diagnostic testing, however, several records with different sweep times may be required.

7.5.3.2 Analogue recording of the impulse response current

Impulse current is normally the most sensitive parameter in failure detection. Therefore, the recorded current waves are the main criteria of the test result.

Depending on the form of the current trace and on the use of linear or exponential sweeps, it may be necessary to use more than one record with different sweep times. The resolution achieved should ensure that

a) as clear a representation as possible is obtained from the oscillograms, including the higher frequency components near the front of the wave;
b) the current record is of sufficient duration to permit detection of any discrepancies occurring late in time. It is difficult to lay down preferred rules for sweep speeds and what is meant by late in time as the response of every transformer is different and the speed is to some extent dependent on the type of winding employed. When recording neutral or winding current, recording should continue at least until the inductive peak has been reached, thus permitting examination of the wave to determine if there has been any change in inductance caused by short-circuiting of turns as a result of insulation failure.

7.5.4 Digital recording of waveshapes

The principle of digital recording is the measurement of voltage or current waveshapes by taking samples during the test at regular time intervals. These samples should be presented directly as raw data for evaluating waveshape parameters (see 7.5.3.1) and also for the assessment of test results based on the comparison of recordings taken at reduced and full impulse voltage levels (see 7.5.3.2). Additionally, the recorded data may also be processed by wave analysing algorithms, for example, for fault analysis in recordings (see clause 10).

During impulse tests, high electromagnetic fields are produced in the vicinity of the test set-up. Protection of the sensitive electronic devices in the digital recording system, the entire processing equipment and its power supply against these fields is required.

The digitizer screens should have a resolution of ≥768 × 1 024 pixels and the printers should have ≥ 300 dots per inch.

7.5.4.1 Digital recording of the impulse voltage waveshape

a) Determination of the impulse voltage waveshape

The preferred period for the presentation of data for the records taken for waveshape determination during preliminary adjustment of test-circuit parameters is ≤10 µs for the wavefront record (longer presentation times may be necessary when testing transformer neutrals). The wavetail record should permit the evaluation of the time to half-value and, on occasions, the amplitude of reversed polarity.

IEC 61083-1 specifies a 9-bit, 60 MHz digitizer as the minimum resolution of the digitizer for the registration of impulse voltage and current waveshapes. When zooming in on 10 µs time-periods or less for the evaluation of the wavefront or for the evaluation of chopped impulses, the use of a 10-bit digitizer and 100 MHz sampling frequency should be considered.

Historically, waveshape evaluation is based on oscilloscopic records, engineering rules and eye evaluation of waveshape parameters. With the application of digital recorders in high-voltage testing of power transformers, a warning with respect to amplitude and time parameters should be given with respect to the evaluation of non-standard waveshapes. In particular, when testing high-power-rated low-voltage windings with resulting unipolar overshoots with frequencies less than 0,5 MHz, IEC 61083-2 is not applicable for the amplitude evaluation of such non-standard waveshapes. Errors in excess of 10 % have been observed due to the built-in curve smoothing algorithms in the digitizers (see figures B.18, B.19 and B.21).

In such cases, careful evaluation of the raw data plots using engineering judgement is required. A parallel measurement of the peak voltage by a peak voltmeter according to IEC 61083-1 is highly recommended.

b) Applied impulse test voltage wave recording

In order to determine the amplitude of the test wave and to permit detection of any fault which may be present

– for full waves, the period for the presentation of sampled data should not be less than 100 µs;

– for chopped waves, a period for presentation of 10 µs to 25 µs is usually found sufficient.

Sampling frequencies of 10 MHz to 20 MHz per channel of the digitizer normally suffice because the maximum frequencies of part winding resonance normally do not exceed 1 MHz to 2 MHz. If high frequencies are observed in the voltage or current traces these are due to parasitic resonance in the measuring circuit or noise in the earthing system. It is therefore recommended that higher sampling frequencies (as mentioned before) be used to discriminate noise in the measuring circuit from the actual behaviour of the test object.

For wave analysis, it is important to take samples over the complete waveshape until the wave is completely damped, using the maximum available memory of the digitizer. It is important to programme the digitizer in such a way that a sufficient number of samples is present to determine the virtual starting-point of the wave.

It is, furthermore, important to use the maximum available resolution of the input amplifiers of the digitizer. For that reason, a number of 50 % pre-shots may be needed to determine the optimum range for the amplitude of the voltage wave and/or the offset for each channel.

Special attention should be given to the amount of overswing to opposite polarity of lightning impulses. When measuring such overswing, clipping of the recorded waveshape may occur by saturation of the input amplifier in the digitizer in the chosen range.

One pertinent recording (see clause 11) is normally sufficient for acceptance tests. For diagnostic purposes, however, the software of the system offers the possibility to examine the wave over the entire sampling time, or part of the wave as all information is stored in the computer memory. The software can subtract the full wave and the reduced wave and show differences on an adjustable magnified scale. However, problems might arise for the fast rising part of the waveshape where the proper time adjustment of the two curves can be difficult to accomplish.

7.5.4.2 Digital recording of the impulse response current

Impulse current is normally the most sensitive parameter in failure detection. Therefore, the recorded current waves are the main criteria of the test result. The presentation of the recordings for the acceptance test are the same as for the presentation of oscillograms in 7.5.2.2.

The stored data in the memory of the digitizer, however, allows for any other presentation of the same recording by zooming in or out at different time scales. Requirements with respect to sampling frequencies and resolution of the digitizers' input channels are the same as given in 7.5.3.1.

In order to benefit from additional mathematical investigation tools, such as transfer function analysis (see clause 10), for the examination of the test results, it is important that the same recording time for the recording of the impulse current and voltage is used.

8 Switching impulse tests

8.1 Special requirements

The response of transformers and reactors to switching impulses is very different because transformers have a complete magnetic circuit and the relatively long duration of the switching impulse therefore allows the establishment of a significant amount of core flux (see IEC 60076-3). This is not the case for reactors for which, in addition, waveshape problems and test procedures are different. Therefore, the two items of equipment are dealt with separately.

8.2 Transformers

8.2.1 Waveshapes

As indicated in IEC 60076-3, there are no strict values specified for the virtual front time of a switching impulse wave. It should, however, be sufficiently long to ensure essentially uniform distribution of voltage. This normally requires front times of ≥100 µs. It is determined by the effective winding capacitance, any load capacitance and the series resistances.

The wavetail is influenced not only by the usual waveshaping components but also by a probable saturation of the core. For most transformers, at full test level, the exponential decay of the wavetail is interrupted by a sudden fall through zero, at a variable time after the crest, due to core saturation. Therefore, the virtual time to half-value is not used to specify the wavetail of the applied switching impulse. Instead, the waveshape is defined by its time above 90 % T_d and by the requirement of the time to first zero passage T_z. $T_d \geq 200$ µs and $T_z \geq 500$ µs, but preferably 1 000 µs, are defined in IEC 60076-3. These quantities are illustrated in figure 3a.

The time taken to saturate the core is dependent on the core size, its initial state of magnetization and the level and waveshape of the applied voltage. Unless the core magnetization state is identical before each switching impulse application at a given voltage level, identical waveshapes on successive applications will not be obtained. In addition, identical waveshapes at reduced and full test levels cannot be obtained. See 8.2.3 for test procedure which reduces the effects of core saturation.

Core saturation does not usually occur on reduced-level voltage applications and may not even occur on full-level applications. When it does occur, its effect on the voltage waveshape may be large or small depending on the amount of saturation involved. For this reason, when switching impulses are applied from the high-voltage side of the transformer, it is possible to establish T_1 and T_d from the reduced voltage applications. T_z cannot be established until the first full-level voltage application is made. When switching impulses are performed from the low-voltage side of the transformer, only T_1 can be established from reduced voltage applications. In this case, T_d and T_z can only be determined from full test-level shots.

It should be noted that there may be significant differences in the shape of the wavetail on different limbs of a transformer due to the different reluctances of the magnetic circuit involved.

8.2.2 Terminal connections and applicable methods of failure detection

8.2.2.1 Terminal connections

In order to comply with the requirements of IEC 60076-3, there is only one admissible test connection for three-phase transformers. This connection is shown in figure 4, which indicates that the neutral should always be earthed and the terminals of the non-tested phases preferably interconnected. (This interconnection of non-tested terminals is not necessary for transformers provided with a delta-connected winding.)

This circuit was selected for three-phase transformers with both three- and five-limb cores to perform simultaneously testing of the phase-to-earth and phase-to-phase insulation with 1,0 p.u. (per unit) and 1,5 p.u. respectively.

The choice of winding to which the test voltage is to be directly applied and the level of that test voltage may normally be left to the manufacturer, commensurate with the requirement that the rated switching impulse withstand level is achieved in the winding with the highest rated voltage.

Short-circuiting of windings not under test is not practicable since the effect of such short-circuiting during the switching impulse test is basically the same as in an induced voltage test.

Whilst the basic switching impulse wave is inductively transferred, the interphase capacitive coupling and the inherent phase capacitances and inductances can cause additional oscillations which are superimposed on the transferred voltages. Figure B.14 gives a clear example of this effect. Hence, the requirement in IEC 60076-3 that a phase-to-phase voltage of 1,5 U will occur when a voltage U is applied to one terminal, is valid only in principle. Therefore, during a test, the interphase voltages are likely to be higher than 1,5 U if no measures are taken at the non-tested terminals to suppress the oscillatory voltages by means of high ohmic impedance earthing. The phase-to-earth voltages at the non-tested terminals can be much higher than 0,5 U.

High ohmic loading of the non-tested phase terminals of the winding system under test and/or at the non-tested winding phase terminals is a convenient means to achieve appropriate damping. However, resistive loading causes a significant lengthening of the wavefront at the non-tested terminals, resulting in a phase-to-phase voltage of less than 1,5 U. This results from the slightly different times at which the maxima of applied (U) and induced (0,5 U) voltages occur. When the loading is too severe (too low a resistance), the tail time of the applied switching impulse is significantly shortened to the extent that saturation effects may not occur.

The requirement that 1,5 times the voltage between phase and neutral shall be developed between phases cannot be met on shell-type and five-limb core-type transformers without delta-connected windings, as the flux cannot be directed through the windings on the non-tested limbs. If no delta windings are available, only 1,0 p.u. phase-to-earth tests can be achieved by short-circuiting and earthing of the winding terminals of the non-tested phases.

Similar considerations with respect to superimposed oscillations are valid also for single-phase auto-transformers.

8.2.2.2 Methods of failure detection

For failure detection, normally only the measurement of the applied voltage is sufficient, but when the test is performed by applying the impulse to an intermediate or low-voltage terminal, the voltage should be measured at the terminal with the highest voltage for equipment U_m. The current flowing to earth through the tested winding can additionally be used.

8.2.3 Test procedures

The test procedure is outlined in IEC 60076-3. This procedure includes reference to measures which may be taken to increase the impulse duration by delaying the possible onset of core saturation.

For the method of direct application to the high-voltage winding, primarily referred to in this guide, the procedure involves the application, to each phase terminal, of

– one negative polarity, reduced test level impulse (between 50 % and 75 % of the switching impulse withstand level);
– introduction of opposite polarity remanence, either by means of positive polarity impulses of approximately 50 % amplitude or direct current application;
– three negative polarity impulses at the switching impulse withstand level with introduction of opposite polarity remanence prior to each impulse.

The preferred method of introducing remanence is the application of opposite (i.e. positive) polarity impulses of approximately 50 % test level. To achieve reasonably identical oscillograms or digital recordings at any test level, it is recommended that the same remanence point should always be established, preferably saturation remanence. This point is reached when the time to the first zero passage remains constant on consecutive impulse applications. The number of the required pre-magnetizing impulses and their level depend on the level of test voltage aimed for. To avoid any problems with external flashovers during this procedure, the level of such positive polarity pre-magnetizing impulses should not exceed 50 % to 60 % of the test voltage.

8.2.4 Recording of tests

8.2.4.1 General

Recording of the voltage of the high-voltage terminal is required during switching impulse testing. However, due to the possible excessive voltages to earth on the non-tested terminals or between phases, explained in 8.2.2, it is advisable to at least check these voltages.

The voltage record will normally also satisfactorily indicate any fault on magnetic coupled windings not directly subjected to the switching impulse. Impulse currents may be recorded and will in many cases give additional information about a fault.

For switching impulse voltage recording, it is preferable to use capacitive types of voltage dividers, as resistive voltage dividers would have an influence on the waveshape and may be thermally overloaded. When resistive voltage dividers are used to check the voltage of the non-tested terminals, they should remain in the circuit because they represent a significant loading of the circuit. Properly calibrated capacitive bushing taps can be employed as voltage dividers.

8.2.4.2 Analogue recording of the impulse voltage waveshape

a) Determination of the impulse voltage waveshape

   For the wavefront record taken for waveshape determination during preliminary adjustment of the test circuit parameters, a sweep which encompasses the peak of the wave is necessary, which normally means 100 µs to 300 µs. For the wavetail record, which is used only to determine the time above 90 % T_d, a sweep time of 500 µs to 1,000 µs is recommended.

b) Applied impulse test voltage wave recording

   In order to determine the amplitude of the test wave and to permit detection of any fault which may be present, the sweep time has to be long enough to encompass the first zero passage. This time is longer than the expected time T_z and is normally 1 000 µs to 2 000 µs. In exceptional cases, even longer sweep times, for example, 2 000 µs to 3 000 µs may be necessary.

8.2.4.3 Digital recording of the impulse voltage waveshape

a) Determination of the impulse voltage waveshape

   It is necessary to take samples over the complete waveshape, from the start to the time where the wave is completely damped, using the maximum available memory of the digitizer. It is important to programme the digitizer in such a way that a sufficient number of samples is present to determine the virtual starting-point of the wave. To record the switching impulse, a sampling frequency of 10 MHz is sufficient. The requirements for the digitizer as mentioned in 7.5.3 for the digital recording of lightning impulses are sufficient for the recording of switching impulses.

It is important to use the maximum available resolution of the input amplifiers of the digitizer. A number of 50 % reduced level impulses are needed to determine the optimum range of the voltage and/or the offset for each channel.

Special attention should be given to the effect of magnetic saturation of the core and the possibility of clipping of voltage and current recordings because of saturation of the input amplifiers of the digitizer.

b) Applied impulse test voltage wave recording

In order to determine the amplitude of the test wave and to permit detection of any fault which may be present, the recording has to be long enough to encompass the first zero passage, that is, longer than the expected time T_z. This normally requires recording times of 1 000 μs to 2 000 μs or 2 000 μs to 3 000 μs in exceptional cases.

8.2.4.4 Analogue and digital recording of the impulse response current

As mentioned in 8.2.2, impulse current may be recorded to possibly trace partial discharges. When this current is measured on the winding to which the impulse voltage is directly applied, whether or not this is the winding on which the specified test voltage level is to be achieved, the current comprises three parts:

– an initial capacitive current pulse;
– a low and gradually rising value of the inductive current component, coincident with the tail of the applied voltage;
– a peak of current coincident with any saturation. This current peak will be coincident with a voltage collapse or decay if it is due to the saturation effect.

Any turn-to-turn or part winding fault will also produce an instantaneous current peak, but with a much more rapid voltage collapse, indicating a flux blockage.

When oscillograms or digital recordings of the impulse response current are taken, it is preferable to employ the same sweep time or sampling time as used for the voltage record.

8.3 Reactors

8.3.1 Waveshapes

The waveshape obtainable on reactors will be of a damped cosine form, without any saturation effects on the tail, since there is no complete ferro-magnetic circuit through the windings. This waveshape should be characterized mainly by its frequency, determined by the reactor inductance and the generator capacitance, and the damping coefficient. However, practice has been to specify reactor waveshapes as for transformers, that is, by T_1, T_d and T_z (see figures 3b and B.16).

The virtual front time is determined, as for transformers, primarily by the effective winding capacitance, additional load capacitance and the series resistance. It should be long enough to ensure approximately uniform distribution throughout the tested winding. For large values of T_1, the damping coefficient will be large thus resulting in a relatively short time T_z. For small values of T_1, T_d will become short and the opposite polarity peak may well approach 75 % of the test voltage level with an ensuing risk of phase-to-earth or phase-to-phase flashover. Due to these implications, it appears logical, as in the case of transformers, to limit the maximum opposite polarity peak to a safe level, of not more than 50 %, and to accept the corresponding values of T_1, T_d and T_z.

Normally the transformer characteristic of $T_d \geq 200$ µs is not a problem for small reactors (<100 Mvar for three-phase reactors with relatively high impedances). For large reactors, T_d and T_z as specified for transformers would require excessive impulse generator extension. For such cases, a minimum value for T_d and T_z should be 120 µs and 500 µs respectively to assure adequate volt-time stress.

8.3.2 Terminal connections and applicable methods of failure detection

8.3.2.1 Terminal connections

Since there is only one winding per phase, the application point for the test voltage is the line terminal of the phase winding which is to be tested. The other terminal of this phase winding should be earthed.

For three-phase reactors, the requirement, as in figure 4, that 1,5 times the voltage between phase and neutral shall be developed between phases, cannot be met. The flux in these reactors cannot be directed through the windings on the non-tested limbs. Hence, the normal impulse test procedures as used for lightning impulse tests are required.

8.3.2.2 Methods of failure detection

For failure detection, as for transformers, normally only the measurement of the applied voltage is sufficient but the current flowing to earth through the tested winding should additionally be used.

8.3.3 Test procedures

Since there is no core saturation effect, the test procedures for reactors is the same as for lightning impulse tests. They comprise

– the determination of the impulse voltage waveshape;
– the application of one negative polarity reduced test level impulse;
– the application of three negative polarity impulses at the switching impulse withstand level without any pre-magnetization measures.

8.3.4 Analogue and digital recording of impulse voltage waveshape and impulse response current

Subject to the waveshape differences described in 8.3.1, the same general principles apply to voltage and current recordings on reactors as for transformers. It is, however, advisable to use sweep times for both voltage and current which cover the second half-cycle of the applied voltage.

For current recordings, it may be advantageous to use, in addition, a shorter sweep time so as to be able to monitor the initial capacitive current in more detail. The basic waveform of the current corresponding to the cosine voltage wave is sinusoidal (see figures 3b and B.16).

9 Interpretation of oscillograms or digital recordings

The basic method for judging the results of a test is by comparison between the test waveforms obtained in a given test sequence. Generally speaking, traces recorded from the same channel, under the same test conditions and using the same test circuit constants, should be identical except in the case of non-linear devices. Different test voltage levels should be compensated by appropriate attenuations to obtain the same recording level.

Annex B contains a number of oscillograms and digital recordings taken during actual tests on transformers and reactors demonstrating fault and non-fault conditions. It is, however, strongly emphasized that similar waveform discrepancies on another unit cannot necessarily be taken as arising from the same cause as the faults will present themselves differently from design to design.

9.1 Lightning impulse

9.1.1 General

Interpretation of oscillograms or digital recordings is based on comparison of the waveshapes of voltages and current records between reduced and rated test voltages or between successive records at rated test voltage. This is a skilled task and it is often difficult to decide the significance of discrepancies, even with considerable experience, because of the large number of possible disturbance sources. Discrepancies of any kind are of concern and should be investigated.

For such an investigation into discrepancies, it is recommended to check first that the test circuit, the measuring circuit and earthing methods are not causing the disturbances. If the disturbances originate in the test circuit, every effort should be made to eliminate them or at least to minimize their effect. It should be remembered that in multi-stage generators, differences in the firing times of the individual stages may give rise to minute changes in the amplitude of current records with high-frequency initial oscillations (without changing the basic frequency). See figure B.13. In the majority of cases, however, these changes are limited to a time period corresponding to 50 % of the wavefront of the applied impulse.

There are sometimes also discrepancies after the peak, which may also originate from the generator, with multiple parallel stage operation, if the discharge circuits are not coincident in time. This may require new setting of the discharge gaps on generators which have both series and parallel gaps.

Secondly, it should be checked that core earthing or any non-linear elements within the test object are not the source of the disturbances. Non-gapped, non-linear resistors may produce a logical and progressive development or change with increasing voltage levels (see figure B.12).

Having eliminated or explained the above sources of discrepancies, variations in the wave-shape of voltage or current records between reduced and rated test voltage or between successive records at rated test voltage, which cannot be proved to originate in the test circuit or in non-linear resistors within the test object, are evidence of insulation failure from the test.

9.1.2 Voltage recordings – Full-wave tests

The oscillograms or digital recordings of the applied voltage are a relatively insensitive means for failure detection. Thus, the detectable discrepancies indicate major faults in the insulation or in the test circuit.

Provided that the time resolution is sufficiently high, a more detailed analysis of discrepancies is possible.

– Direct faults to earth near the terminal under test will result in a rapid and total collapse of the voltage. A progressive but nevertheless total flashover across the winding under test will result in a somewhat slower voltage collapse, normally occurring in a stepped manner (see figure B.1).
– A flashover across part of the winding will reduce the impedance of the winding, thus resulting in a decrease of the time to half-value. Characteristic oscillations will also occur on the voltage wave at the moment of flashover (see figures B.1 to B.5).
– Less extensive faults, such as breakdown of coil-to-coil or even turn-to-turn insulation are normally not recognizable on the voltage recordings but may sometimes be detected as high-frequency oscillations; current records will normally detect these faults. See figure B.6. Likewise, incipient faults at or near the terminal under test may also give only small indications on the oscillograms or digital recordings.

Transferred voltage recordings will also indicate the above-mentioned faults. The sensitivity of this measurement is higher than that of the applied voltage.

9.1.3 Current recordings – Full-wave tests

Oscillograms or digital recordings of the impulse response current are the most sensitive means for failure detection. However, this sensitivity is accompanied by the possibility of the recordings indicating a number of effects not directly associated with failure. Some possibilities have been identified in 9.1, which may be responsible for erratic bursts of oscillations or wavefront changes on current traces and should be investigated.

Major changes in current records such as amplitude and frequency changes normally indicate part winding breakdowns within the tested winding, between windings or to earth (see figure B.1). The form of the change will be different depending on the method of failure detection employed. Currents may increase or decrease and the direction of the change together with the method of fault detection will give guidance on the nature and location of the fault (see figure B.3).

A significant increase, combined with a change in superimposed frequency in a neutral current is indicative of a fault within the tested winding whilst a decrease indicates a fault from the tested winding to an adjacent winding or to earth.

Capacitively transferred current will, for faults in the tested winding or to earth, show an instantaneous change in polarity. There will also be a change in basic frequency and there may be a decrease in amplitude. A fault from the tested winding to an adjacent winding will show an instantaneous increase in amplitude in the same polarity sense and a change in basic frequency.

Small, local, jagged disturbances, perhaps spread over 2 μs or 3 μs, are a possible indication of severe discharge or partial breakdown in the insulation between turns or coils or coil connections. For windings of small series capacitance, that is, exhibiting essentially travelling wave behaviour, it may be possible to identify the source of disturbances by evaluating the time difference between the arrival at the neutral of the capacitive and the travelling wave disturbances.

9.1.4 Voltage and current recordings – Chopped-wave tests

Comparison of the chopped-wave recordings after the instant of chopping is not normally possible unless the instants of chopping are almost identical. Similar but not necessarily identical instants of chopping are achieved by use of triggered-type chopping gaps (see figure B.10). Even small differences in the instant of chopping, can, for some transformers, give rise to marked differences in the oscillation pattern after the chop (this pattern being a superposition of the transient phenomena due to the front of the original impulse and the chopping) and these differences may confuse comparison between the records of successful applications and those where a fault exists (see figure B.11).

When using digital recording techniques, the transfer function analysis as described in clause 10 may be helpful to eliminate this confusion (see figure B.17).

Any changes in the frequency of the voltage and current recordings after the chopping should be investigated. These changes may be caused by either a flashover in the return loop to the laboratory earth or an internal failure in the test object

When making the chopped wave test, failure of the chopping gap to chop, or any external part to spark over, although the voltage recording shows a chopped wave, gives a definite indication of a failure either within the test object or in the test circuit.

Provided that the time to chopping is reasonably identical from one voltage application to another, failures during this test will be detectable both in the voltage and current recordings by differences in the oscillations after chopping. See figures B.8 and B.9. There are, however, cases where the fault occurs before the instant of chopping and then the same considerations apply as for full-wave tests (see figures B.2 and B.7).

9.2 Switching impulse

9.2.1 Voltage recordings

In switching impulse tests, owing to the uniform distribution of voltage throughout the winding, the fault normally involves major deterioration in the form of a short circuit between sections, parts of a winding or even between windings or to earth. These types of fault cause a significant change in the voltage wave either as a complete collapse of the wave or a shortening of the tail or, sometimes, as a temporary dip in the trace. Hence, the voltage records on switching impulse tests are a sufficiently sensitive means for detection of most faults (see figure B.15).

For transformers, any part-winding defect (turn-to-turn failure, disc-to-disc breakdown, or breakdowns in tapping windings) will result in a flux blockage and will easily be detected by voltage and current records.

For gapped core reactors, which have only one winding per phase and no closed magnetic loop, the detection of turn-to-turn faults may be very difficult, or faults may be even left undetected. Here a higher resolution of the capacitive current flowing to earth, or a second current record (the tank current), may be helpful. In such cases, higher resolution recording to cover the time to peak and to the opposite polarity of the applied cosine wave is recommended.

Any wavetail shortening in transformer tests is usually quite distinguishable from variation in the length of the wavetail resulting from differing initial states of core magnetization on successive applications; nevertheless, the closer the initial states can be matched, the easier it becomes to distinguish between a fault and a non-fault condition.

9.2.2 Recordings of the impulse response current

The general waveform of the current record has been described in 8.2.4.4 for transformers and in 8.3.4 for reactors. Except at the start of the wave or, in the case of transformers, in the vicinity of core saturation, sharp changes of current occurring at the same time as any distortion of the voltage wave are indicative of failure. With the nature of faults to be expected, current records are as sensitive as voltage records.

10 Digital processing, including transfer function analysis

With the introduction of digital recording techniques in LI and SI impulse testing, there are now additional tools available for failure analysis.

In transfer function analysis, the real time records of both the applied voltage $U(\mathrm{t})$ and the resulting impulse response current $I(\mathrm{t})$, either at the transformer neutral or at the shorted non-tested winding to earth (capacitively transferred current), can be transferred by Fast Fourier Transformation (FFT) algorithms to the frequency domain, respectively $U(\omega)$ and $I(\omega)$.

Then voltage and current spectra ($U(\omega)$ and $I(\omega)$) are mathematically treated as follows:

a) by division of $I(\omega)/U(\omega)$ to form the transfer admittance function,

or

b) by division of $U(\omega)/I(\omega)$ to form the transfer impedance function.

For the passive network of a transformer, both the admittance function and the impedance function are considered as a characteristic function in the frequency domain and should be independent of the waveshape. However, since the voltage spectrum $U(\omega)$ does not exhibit any zero points, the transfer admittance function $I(\omega)/U(\omega)$ is preferably used in transfer function analysis.

Examples of such transfer function are given in figure B.17.

From the quadrupol[1)] theory the failure indications are derived as follows for the admittance function.

1) Any shift of significant poles in the transfer function is indicative of a part-winding breakdown.
2) Any flattening of the poles is said to be indicative of partial discharges.

1) The quadrupol theory is a mathematical tool to describe the relationship between input and output quantities in a linear electrical network in the time and frequency domain.

However, changes in the impulse current and/or the applied voltage which do not lead to a change in transfer admittance function, indicate a test circuit problem rather than a test object problem and hence is a tool to differentiate between internal and external failures.

It is emphasized that this technique is not fully proven for all cases and at present is only recommended as an additional aid to interpretation of results. The final acceptance of test results is still based on comparison of waveforms as stated in 7.5.

Digitizers have been used in impulse testing since the 1980s. However, the literature and experience regarding transfer function analysis was for many years contradictory. There are several reasons for these contradictions, namely

a) transformers and in particular the lightning impulse test circuits cannot be represented by a lumped linear circuit element for which quadrupol theory is fully applicable;
b) digitizers may have non-standardized in-built filters to filter noise from the signal which may
   - result in incipient fault indications being filtered out and not recognized;
   - affect the waveshape independence of the admittance function;
c) the good/bad criteria for the deviations in the different fault conditions have not yet been established to an adequate degree.

This new technology represents a very powerful tool for the future, because it may also be used for on-line condition monitoring, both for dielectric defects and for mechanical defects after severe short-circuits.

In the following a few example recordings, both for real time and transfer function analysis, are presented.

Case 1: Example recordings of digitally evaluated non-standard waveshapes

- For non-standard waveshape 1,44/46 µs with 19 % overshoot, evaluated by tangent through tail decay according to IEC 60060-1, see figure B.18. Here the error in amplitude evaluation may be greater than 10 % due to the unknown in-built curve smoothing algorithms of digitizers.
- For non-standard waveshape 2,48/50 µs, having superimposed oscillations with >50 % amplitude and frequency less than 0,5 MHz, see figure B.19. Here the digitizer evaluated the time to half-value as 5 µs, based on the first passage of the superimposed oscillation, whereas evaluation according to IEC 60060-1 shows 50 µs.
- For non-standard chopped wave on a layer type winding, see figure B.20. Here the layer impedance avoids rapid collapse and oscillations around zero of the chopped wave to earth. (Compare oscillograms or digital recordings in figures B.8 to B.11 with figure B.20.)
- For comparison of non-standard waveshapes by digitizers of different make from the same recording: in the example in figure B.21, a difference of 7 % in amplitude (109,9 kV versus 102,3 kV) and of 9 % in the T_1 parameter (2,55 µs versus 2,34 µs) is found. The difference in the T_2 parameter is not explainable. The reading of the calibrated parallel peak voltmeter was 110 kV.

Case 2: Responses from test-circuit problems

- For test-circuit problems caused by a sparkover to earth from a measuring cable, see figure B.22a. The capacitively transferred current from the LV winding sparks to a different earth than the tank and generator earth, resulting, after comparing with the reduced full-wave test, in
  a) no indication in the voltage;
  b) clear indication in the current;
  c) clear indication in the transfer function analysis.
- In the transfer function, flattening of poles is present, but no change in frequency. This indicates discharges.
- After correction of the fault in the measuring cable, the impulse test was repeated. Figure B.22b shows a perfect match between the transfer functions at reduced- and full-wave impulse tests.

Case 3: Responses from test object failures

- A failure digital recording of a tap changer lead flashover between taps is shown in figure B.23a. The real time recordings of voltage and current at the full impulse and the transfer function show significant changes compared to the reduced full-wave impulse test.
- For failure digital recording between a coarse and a fine regulating winding, see figure B.23b. Significant changes occur in all real time and transfer function records.

As can be seen from the records in all previously shown examples, all defects were also detected by the real time records.

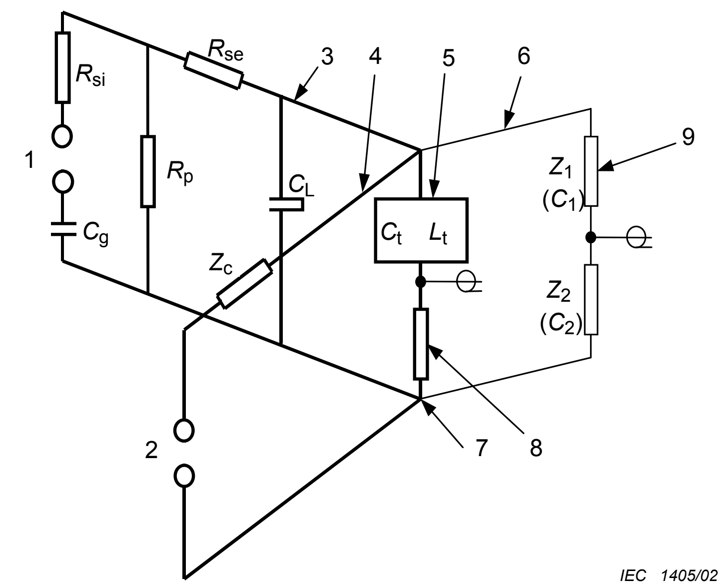
11 Impulse test reports

A report of the impulse tests conducted on the test object should include at least the following information.

a) General information, including
   - type, rating and voltage of the equipment tested;
   - serial number;
   - tap position on which the test is carried out;
   - place and date of the test;
   - manufacturer's test engineer;
   - purchaser's witnessing engineer;
   - standard to which the equipment is tested;
   - specified test levels and waveshapes.
b) A tabulation showing impulse tests conducted on each terminal including
   - type and magnitude of test waves;
   - numbering of recordings for identification and easy cross-referencing;
   - actual test voltages for LI, full or chopped waves, and for SI;
   - actual set-up parameters (internal and external) for the impulse generator;

– actual waveshape parameters for LI (T_1, T_2, T_c) and for SI (T_1, T_d, T_z);
– a diagram of the connections for each test, including
  – terminal markings;
  – which terminal the impulse is applied to;
  – earthing arrangements of the non-tested terminals of the tested phase and of the non-tested phases, including values of any earthing resistances or impedances;
– test-circuit details;
– voltage and current measurement positions and arrangements.

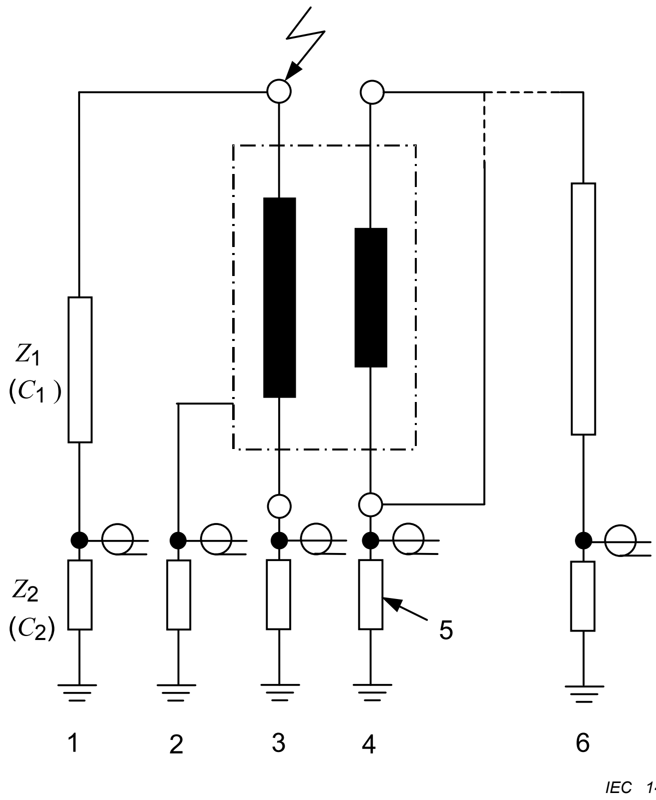
c) Reproductions of the pertinent recordings taken during the tests are an important part of the test report. When specified, these recordings should be properly identified and arranged so that the necessary comparisons between full waves and chopped waves can be easily made. The scaling of each axis (that is, magnitude and time) should be shown on every oscillogram or digital recording.



Key

1	impulse generator	C_g	generator capacitance
2	chopping gap	C_L	loading capacitance
3	main circuit	C	effective test object capacitance
4	chopping circuit	L_t	effective test object impedance
5	test object	R_{si}	internal series resistance
6	voltage measuring circuit	R_{se}	external series resistance
7	reference earth	R_p	parallel resistance
8	current shunt	Z_c	additional impedance in the chopping circuit
9	voltage divider	Z_1 (C_1)	impedance (capacitance) of the high-voltage arm of the voltage divider
		Z_2 (C_2)	impedance (capacitance)of the low-voltage arm of the voltage divider

Figure 1 – Typical impulse test circuit



Key

1 voltage measuring circuit

2 tank current

3 neutral or winding current

4 capacitively transferred current

5 current shunts

6 voltage measuring circuit and transferred voltage

Z_1 (C_1), Z_2 (C_2) impedances (capacitances) in the voltage divider (see also figure 1)

Figure 2 – Lightning impulse test terminal connections and applicable methods of failure detection

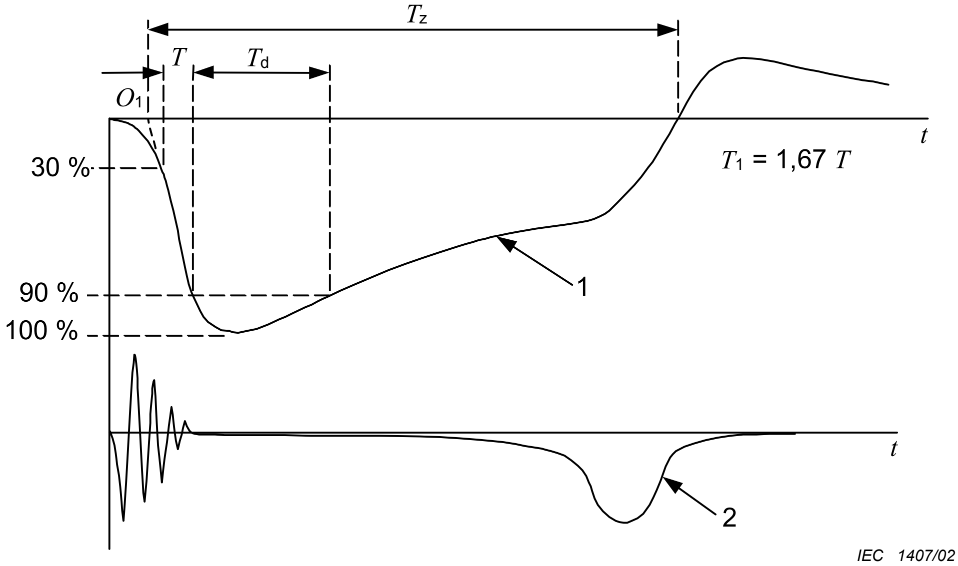


Figure 3a – Transformer switching impulse waveshapes

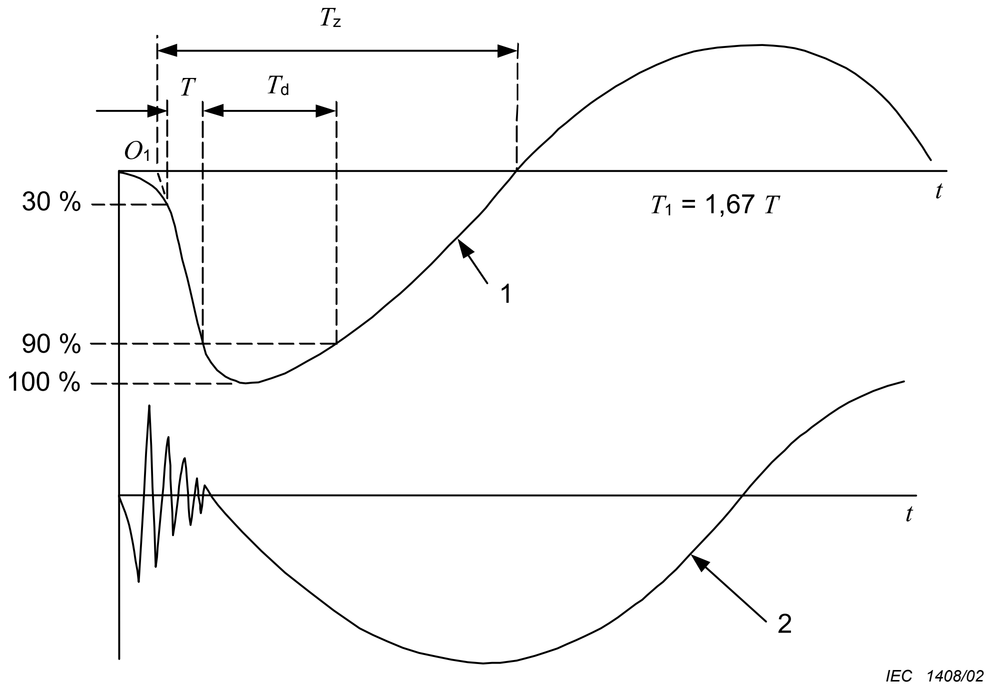


Figure 3b – Reactor switching impulse waveshapes

Key

1 voltage waveshape

2 current waveshape

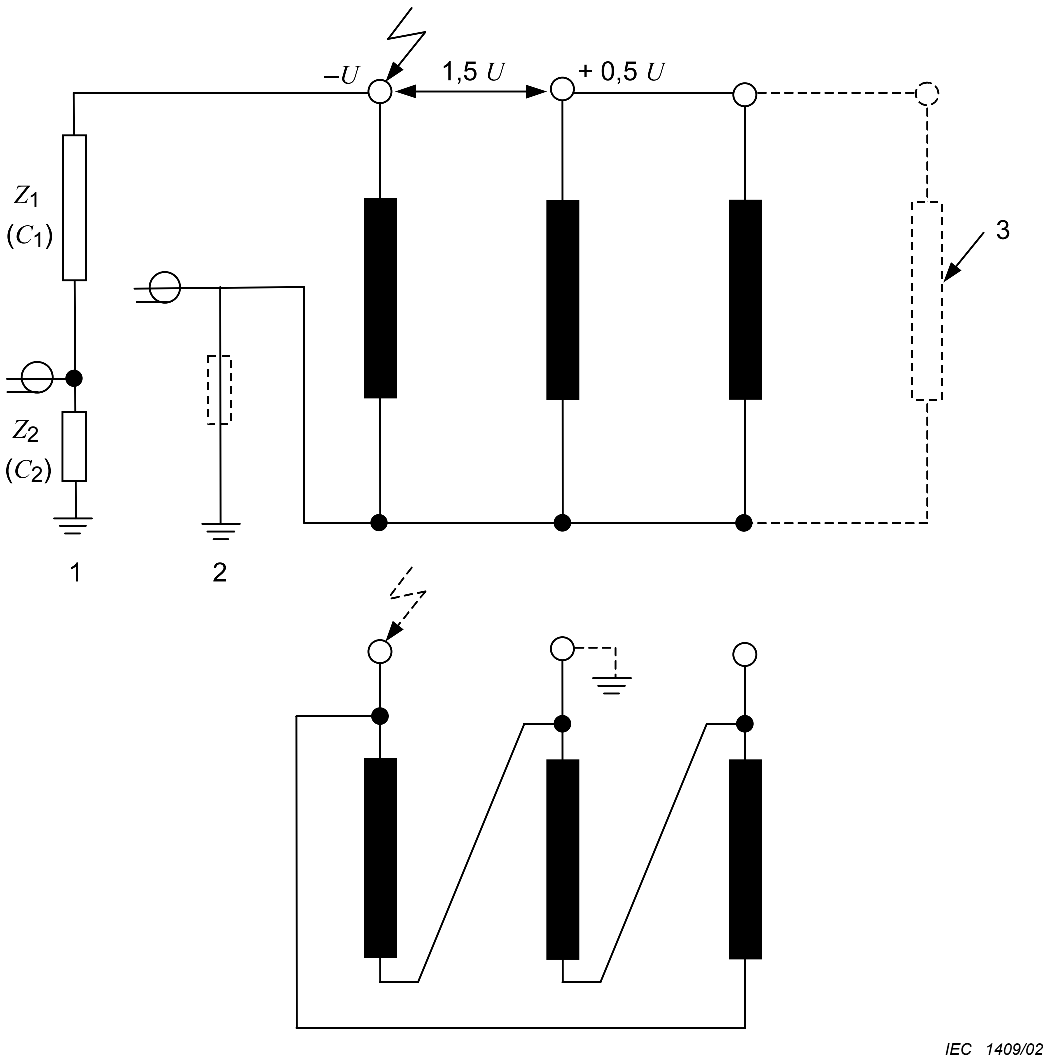
T time between the instant when the impulse is 30 % and 90 % of the peak value

T_1 virtual front time

T_z time to first zero passage

T_d time above 90 % of the specified amplitude

Figure 3 – Transformer and reactor switching impulse waveshapes



Key

1 voltage measuring circuit

2 current measuring circuit

3 loading resistor, see 8.2.2.1

Z_1 (C_1), Z_2 (C_2) impedances (capacitances) in the voltage divider (see also figure 1)

NOTE An alternative application of impulse to delta-connected winding is shown dotted.

Figure 4 – Switching impulse test terminal connections and methods of failure detection

Annex A
(informative)

Principles of waveshape control

A.1 General

Impulse waves are generated by an arrangement that charges a group of capacitors in parallel and then discharges them in series. The magnitude of the voltage is determined by the initial charging voltage, the number of capacitors in series at discharge, and the regulation of the circuit. The waveshape is determined largely by the capacitances and resistances of the generator and the impedance of the load.

The principles of how to control waveshapes in lightning impulse testing of transformers are indicated by means of the simplified diagrams given in figures A.1 and A.2. They need to be subdivided into two major aspects:

– for high-impedance windings;
– for low-impedance windings.

A.2 High-impedance windings (L_t > 100 mH)

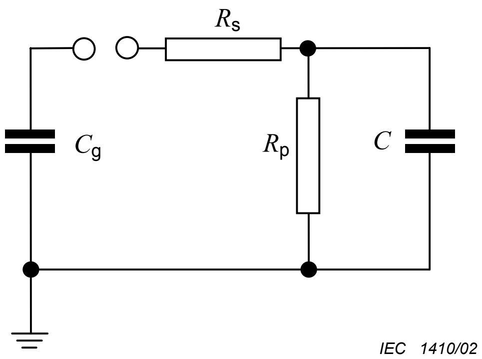


Figure A.1a

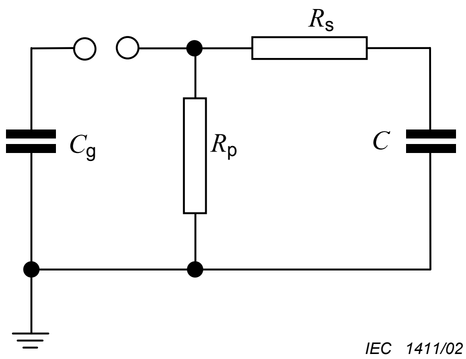


Figure A.1b

Key

C_g generator capacitance

$C = C_t + C_L + C_1$ (see figure 1)

$R_s = R_{si} + R_{se}$, total series resistance (see figure 1)

R_p parallel resistance (see figure 1)

Figure A.1 – Waveshape control for high-impedance windings

The front time will be

$$T_1 \approx 3 \times \frac{R_s R_p}{R_s + R_p} \times \frac{C_g C}{C_g + C} \quad \text{(figure A.1a)} \tag{A.1}$$

or

$$T_1 \approx 3 R_s \times \frac{C_g C}{C_g + C} \quad \text{(figure A.1b)} \tag{A.2}$$

And the time to half-value will be

$$T_2 \approx 0{,}7(R_s + R_p)(C_g + C) \quad \text{(figure A.1a)} \tag{A.3}$$

or

$$T_2 \approx 0{,}7 R_p (C_g + C) \quad \text{(figure A.1b)} \tag{A.4}$$

For $R_p >> R_s$ and $C_g >> C$:

$$T_1 \approx 3 R_s \times C \text{ and } T_2 \approx 0{,}7 R_p \times C_g \tag{A.5}$$

In general, both front and tail parameters are adjusted according to these principles applicable for purely capacitive loads. It should, however, be pointed out that the effective transformer capacitance C_t, included in the values of C, is a different physical quantity for front and tail considerations.

For the front time, C_t can be calculated as $C_t \approx C_B + \sqrt{(C_s C_e)}$ where C_B is the bushing capacitance, C_s is the winding series capacitance and C_e is the winding earth capacitance.

For the wavetail, C_t can be estimated as C_B plus part of C_e, dependent on the initial voltage distribution. Evidently, the value of C_t for tail considerations is of minor importance in most practical cases (see equation (A.5)).

For windings of effective inductances L_t in the range 20 mH to 100 mH, the winding impedance considerably reduces the discharge time constant ($\tau = R_p C_g$). In these cases, the value of T_2 cannot directly be adjusted according to equation (A.5). To account for this effect, experience has shown that R_p has to be increased to a value two to ten times greater than the value derived from equation (A.5).

A.3 Low-impedance windings (L_t < 20 mH)

For the front adjustments, the same applies as for high-impedance windings.

For wavetail adjustments, the test object can be represented by its effective inductance as indicated in figure A.2.

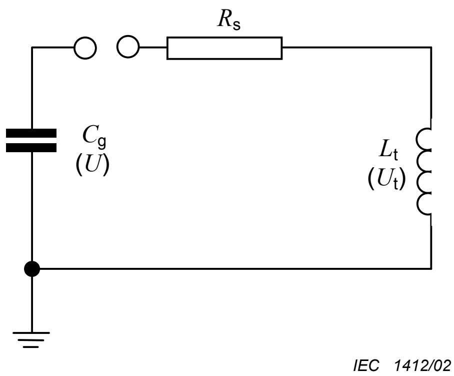


Figure A.2 – Wavetail control for low impedance windings

The test voltage U_t will be oscillatory or exponential, depending on the value of the damping coefficient k of the circuit. Critically (k = 1) or over-critically (k > 1) damped circuits result in exponential curves. However, these are normally not applicable since the corresponding resistance values give unacceptably long front times.

When $k < 1$, the test voltage is given by

$$U_t = U e^{-\alpha t}(\cos\omega t - \frac{\alpha}{\omega}\sin\omega t) = \frac{U}{\cos\varphi} e^{-\alpha t}\cos(\omega t + \varphi) \quad \text{(A.6)}$$

where

$\omega^2 = \omega_0^2 - \alpha^2$

$\omega_0^2 = \dfrac{1}{L_t C_g}$

$\alpha = \dfrac{R_s}{2L_t}$

$\tan\varphi = \dfrac{\alpha}{\omega} = \dfrac{k}{\sqrt{1-k^2}}$

and the damping coefficient

$$k = \frac{\alpha}{\omega_0} = \frac{R_s}{2\sqrt{\dfrac{L_t}{C_g}}}$$

This voltage constitutes a damped oscillating wave (shown in figure A.3).

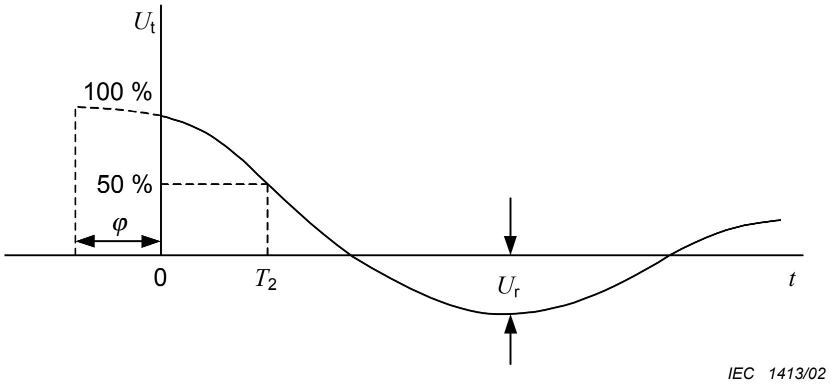


Figure A.3 – Damped oscillation

For a first estimation of T_2, R_s is assumed to be zero. Then equation (A.6) becomes:

$U_t = U\cos\omega_0 t$ and the time to half-value is given by

$$T_2 = \frac{1}{6} \times \frac{2\pi}{\omega_0} = \frac{\pi}{3}\sqrt{L_t C_g} \qquad \text{(A.7)}$$

but this theoretical condition would give an undamped oscillation with an opposite polarity peak of 100 %.

Such high opposite polarity oscillation may overstress inter-turn and inter-winding insulation due to high oscillatory stresses which can trigger partial discharges and enhanced electrode mechanisms only due to testing limitations. The opposite polarity peak U_r should therefore be limited to 50 % of the initial peak voltage.

With the limitation of the 50 % opposite polarity peak U_r, a considerable degree of damping has to be introduced, with the effect that the time to half-value will then be shorter than the value produced by equation (A.7). For this case, the damping factor k = 0,25 and the time to half-value will be

$$T_2 = \sqrt{0{,}5 L_t C_g} \qquad \text{(A.8)}$$

Equations (A.7) and (A.8) give guidance for the control of the wavetail by adjustment of the inductance of the test object L_t or of the generator capacitance C_g.

L_t is influenced by the connection of the non-tested windings. With the non-tested windings short-circuited and earthed (usual connection), L_t is the leakage inductance of the transformer. Testing in this configuration generally produces the greatest stress to the insulation between windings or portions of windings, even if a shorter tail results. However, the short tail will not stress the middle of the winding to earth so much as some other possible configurations since the short tail will not sustain the voltage for a long time.

The effective inductance can be increased by resistance loading of the non-tested windings, with the limitation, however, that the voltages at the non-tested winding terminals should not exceed 75 % for star-connected windings or 50 % for delta-connected windings of their associated lightning impulse withstand level(s).

C_g can be altered by series or parallel connection of the stages of the impulse generator. According to equation (A.9), the required minimum generator capacitance will be

$$C_g \approx 2\frac{T_2^2}{L_t} \tag{A.9}$$

There are, however, cases where the condition of equation (A.9) cannot always be met because of extremely low values of L_t or where L_t can no longer be increased by resistance earthing of the non-tested winding terminals, because of the voltage limitation referred to above. In these cases, the discharge time constant of the circuit is given by

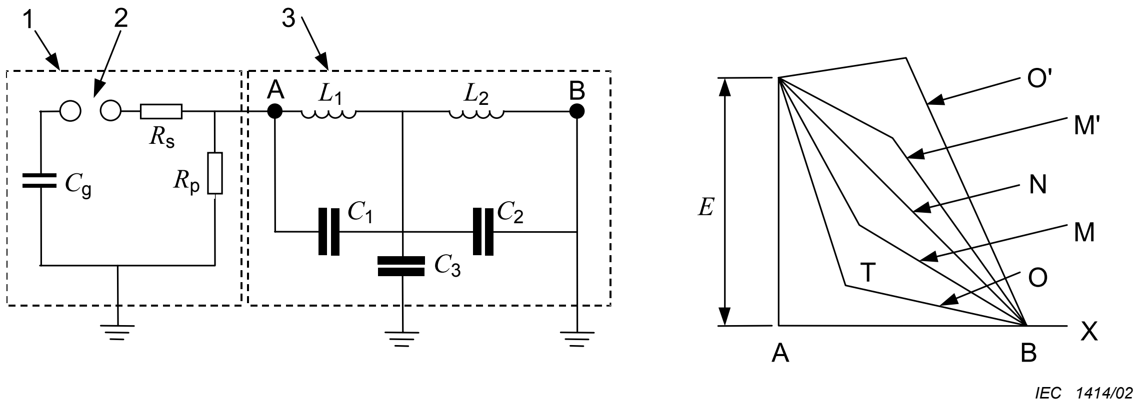
$$\tau = \frac{L_t}{R_s} \tag{A.10}$$

This equation indicates another way of adjusting the wavetail. However, severe reduction of R_s will result in excessive overshoot or superimposed oscillations at the crest of the impulse wave and also, as described earlier, in an excessive opposite polarity peak. In such cases, it is recommended that additional load capacitance C_L is used for wavefront control. The load capacitance will then reduce the adverse effects of a small series resistor R_s.

If the above-mentioned methods of wavetail control are still not sufficient to attain the proper time to half-value, a compromise is necessary between either accepting a shorter time to half-value or resorting to resistance earthing at the non-tested terminal(s) of the winding(s) under test, according to figure A.6. Here again, the 75 % voltage limitation on the non-tested terminal(s) for star-connected windings and 50 % for delta-connected windings of their associated lightning impulse withstand level(s) applies. Preference should be given, however, to a shorter time to half-value.

Item 3 in figure A.4 shows the equivalent transformer with one end of the winding solidly earthed. If the through capacitances C_1 and C_2 are large compared to the capacitance C_3 to earth then a voltage distribution similar to curve M in the graph will result. The final distribution is shown by line N, which means that the envelope of oscillation will be between curves M and M'. When the through capacitances are extremely small compared to the capacitance to earth, then a voltage distribution similar to curve O will occur, which will result in an envelope of oscillation between curves O and O'. With this configuration, there are portions of the winding that may exceed the applied voltage to the line terminals, but generally these windings have long time constants, and the time for point T to oscillate to its maximum is usually long enough that the voltage applied at the terminals has decreased to 50 % of the crest value. This configuration does not produce a sustained stress from winding to earth, but it does stress the insulation within the winding.

This test configuration is very suitable for current measurements since there is no increase in the circuit resistance and the circuit therefore has good response to high-frequency disturbances.



Key

1 impulse generator

2 spark gap

3 transformer

X earth

A winding terminal

B winding neutral end

E voltage amplitude on the winding terminal

C_1, C_2 through capacitances

C_3 capacitance to earth

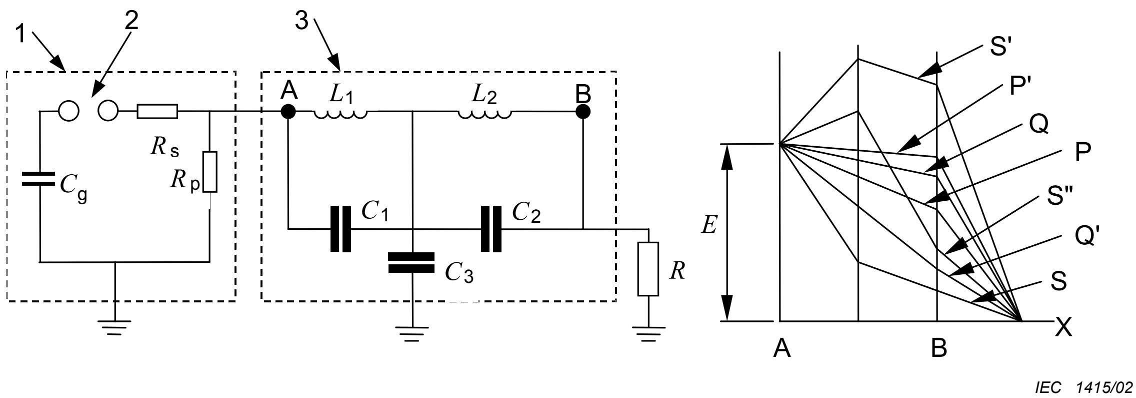
C_g, R_s, R_p (see figure 1)

L_1, L_2 inductances

Figure A.4 – Effects due to short length of wavetail

Another possible configuration is to insert a resistance in the earthed end of the winding under test. This configuration tends to change turn-to-turn and coil-to-coil stresses, the amount of change depending on the winding time constants. Item 3 in figure A.5 shows the typical equivalent network of a transformer with the untested end of the winding earthed through a resistor. If the through capacitances C_1 and C_2 are extremely large compared to the capacitance C_3 to earth, a distribution similar to curve P in the graph will result. The final distribution will be similar to curve Q, where all, or almost all, of the voltage appears across the resistor. The envelope of oscillation will then be between curves P and P'. When the capacitance to earth is large compared to the through capacitance, an initial distribution similar to curve S in then graph will occur and the final distribution can again be assumed to curve Q. The envelope of oscillation is now between S and S'. Again it is possible to produce excessively high voltages to earth in parts of the winding. It is general practice to insert only enough resistance to produce an adequate length tail and the voltage appearing across the resistor is limited to not more than 75 % of the associated lightning impulse withstand level. If in the last example, the resistance required to produce an adequate length tail had been smaller, the final distribution line would be lowered to Q', and the envelope of oscillation would then be between S and S''. The tail length and the voltage across the resistance should be measured to determine the value of resistance to be used.

This test configuration applies the proper waveshape to the line-end insulation and is suitable for earth current measurements, although the resistance may reduce slightly failure detection sensitivity. Initially, the full impulse voltage is applied across the winding and resistance in series; therefore, the stress across the winding will be reduced.



Key

1 impulse generator

2 spark gap

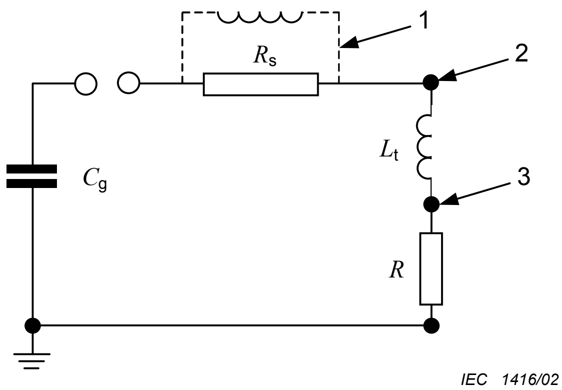
3 transformer

X earth

Figure A.5 – Winding earthed through a resistor

Inserting an inductance between the impulse generator and the winding being tested, sometimes in parallel with R_s (see figure A.6) increases the total circuit inductance and can often increase the tail time beyond that available with the impulse generator alone. This configuration relies on a transfer of energy to the inductor from the impulse generator during the front portion of the wave and a transfer of energy from the inductor to the winding during the tail portion of the wave. The amount of improvement in the tail time with this configuration is dependent on the characteristic of the winding and the values of inductance available.

Nearly the same considerations apply for the adjustment of the switching impulse front time. However, in this case the effective transformer capacitance C_t for the longer front time is equal to the effective winding earth capacitance C_e.



Key

1 A further method of improving the time to half-value is being developed which uses an additional inductor in parallel with R_s, thus increasing the total circuit inductance.

2 tested terminal

3 non-tested terminal

Figure A.6 – Resistance earthing of low-impedance windings

Annex B
(informative)

Typical oscillograms and digital recordings

The oscillograms and digital recordings of fault and non-fault conditions reproduced on the following pages are extracted from records of actual tests on core-type power transformers with concentric cylindrical windings and on shunt reactors. Attention is again drawn to the fact that whilst these oscillograms are typical, it cannot be assumed that a discrepancy found on another transformer or reactor of different voltage, design and manufacture, although apparently similar to one illustrated herein, is caused by an identical fault. The intention of illustrating particular faults is to give general guidance only.

Table B.1 – Summary of examples illustrated in oscillograms and digital recordings

Figure	Example	Clause
Lightning impulse test		
Full-wave faults		
B.1	Breakdown, line to neutral, across tested high-voltage winding	9.1.2; 9.1.3
B.2	Breakdown, between discs, at entrance to tested high-voltage winding	9.1.2; 9.1.4
B.3	Breakdown, interlayer, in course-step tapping winding	9.1.2; 9.1.3
B.4	Breakdown between tapping leads of outside tapping winding	9.1.2
B.5	Breakdown across one section in a fine-step tapping winding	9.1.2
B.6	Breakdown between parallel conductors of a main high-voltage winding	9.1.2
B.7	Breakdown between bushing foils	9.1.4
Chopped-wave faults		
B.8	Breakdown between turns in tested main high-voltage winding	9.1.4; 10
B.9	Breakdown between turns in a fine-step tapping winding	9.1.4; 10
Chopped waves – Effects of differences to chopping		
B.10	Tests with identical times to chopping	9.1.4; 10
B.11	Tests with large and small differences in times to chopping	9.1.4; 10
Non-faults causing discrepancies		
B.12	Effect of non-linear resistors in tap-changer	9.1.1
B.13	Effect of generator firing differences	9.1.1
Switching impulse tests		
B.14	Satisfactory test on a transformer	8.2.2.1
B.15	Breakdown of tested main high-voltage winding of a transformer	9.2.1
B.16	Satisfactory test on a reactor	8.3.1; 8.3.4
Transfer function analysis		
B.17	Comparison of the transfer function of a full wave and a chopped wave	9.1.4; 10

Table B.1 *(continued)*

Evaluation of non-standard waveshapes		
B.18	Influence of curve smoothing algorithms of digitizers	7.5.2; 7.5.4.1; 10
B.19	Evaluation with superimposed oscillations	7.5.2; 7.5.4.1; 10
B.20	Non-standard chopped wave on a layer winding	7.2.2; 10
B.21	Comparison of non-standard waveshapes with different digitizers	7.5.2; 10; 7.5.4.1
Responses from test-circuit problems		
B.22	Test-circuit problem caused by sparkover to earth from a measuring cable	10
Responses from test object failure		
B.23	Full lightning impulse, failure between taps of tap changer and between coarse and fine tapping windings	10

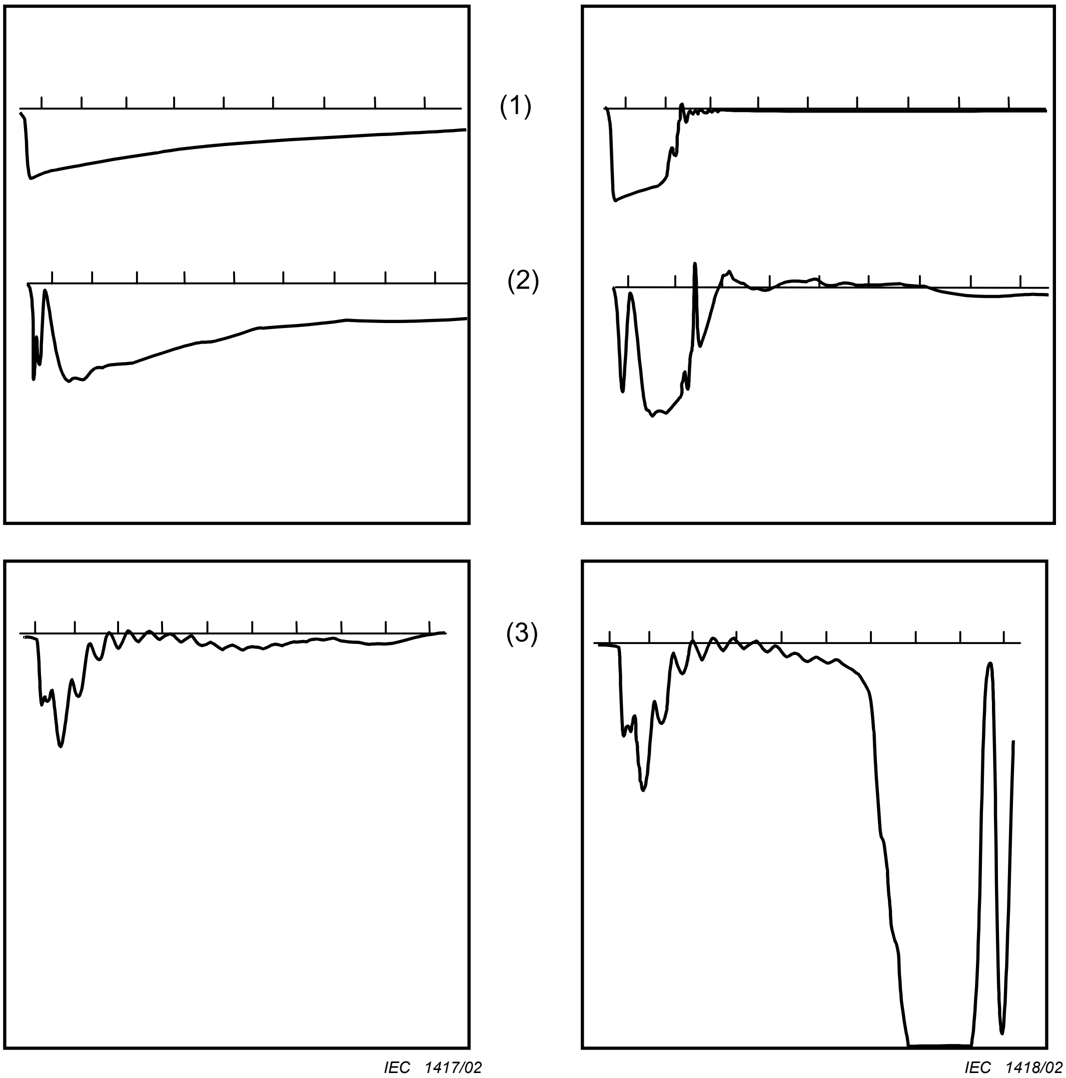


Figure B.1a – Reduced full wave (75 %) without fault

Figure B.1b – Full wave (100 %) with fault

(Amplitudes not equalized)

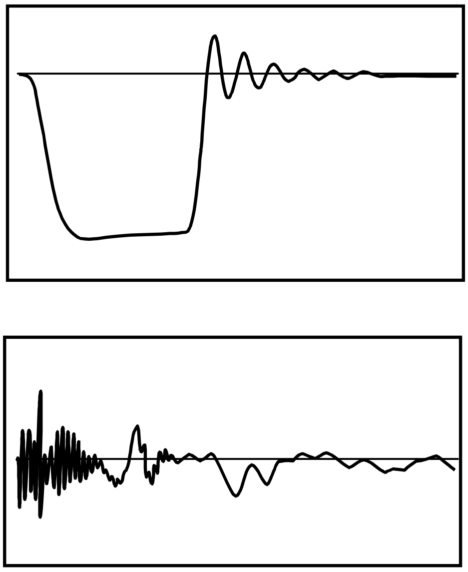
Key

1 applied impulse, 100 µs sweep

2 voltage transferred to low-voltage winding, 100 µs sweep

3 neutral current, 25 µs sweep

Figure B.1 – Lightning impulse, full-wave failure – Line-to-neutral breakdown across high-voltage winding of 400 kV generator transformer



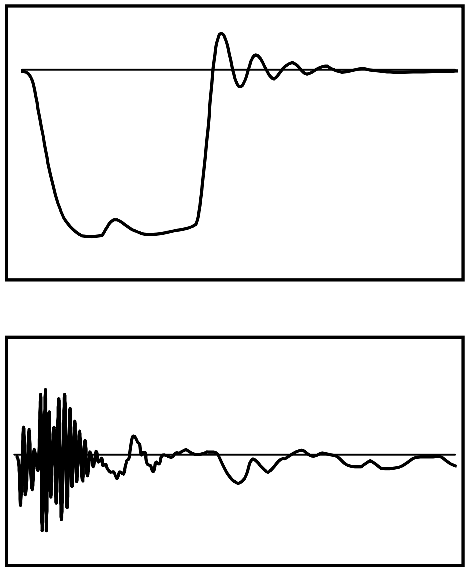


Figure B.2a – Chopped wave (100 %) without fault (Note 1)

Figure B.2b – Chopped wave (100 %) with fault (Notes 1 and 2)

Key

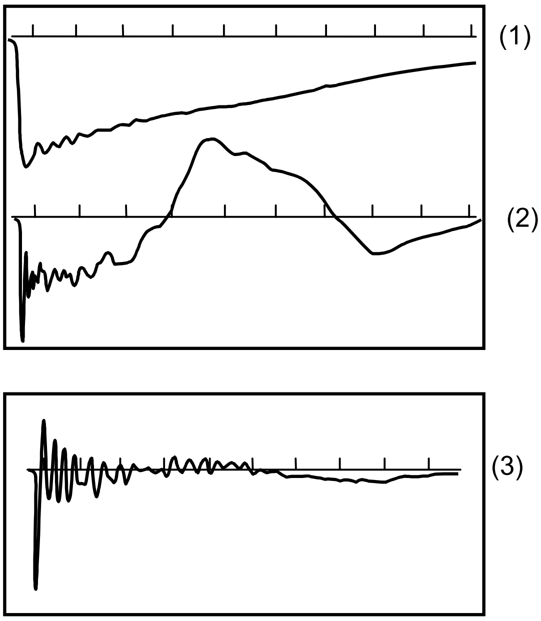
1 applied impulse, 10 µs sweep

2 neutral current, 100 µs sweep

NOTE 1 Since failure occurred before the instant of chopping it is therefore regarded as a full-wave failure.

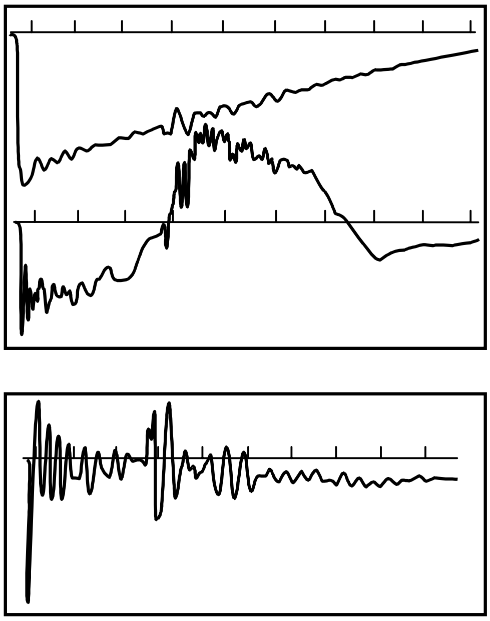
NOTE 2 Failure after approximately 2 µs clearly indicated in the voltage and neutral current oscillograms.

Figure B.2 – Lightning impulse, full-wave failure – Breakdown between discs at entrance to high-voltage winding of 115 kV transformer



IEC 1421/02

Figure B.3a – Reduced full wave (62,5 %) without fault



IEC 1422/02

Figure B.3b – Reduced full wave (75 %) with fault

(Amplitudes not equalized)

Key

1 applied impulse, 100 μs sweep

2 capacitively transferred current from the shorted, adjacent winding to earth, 100 μs sweep

3 neutral current, 100 μs sweep

NOTE Failure after 30 μs, clearly indicated in voltage, capacitively transferred current and neutral current oscillograms.

Figure B.3 – Lightning impulse, interlayer breakdown in coarse-step tapping winding of a 400/220 kV transformer

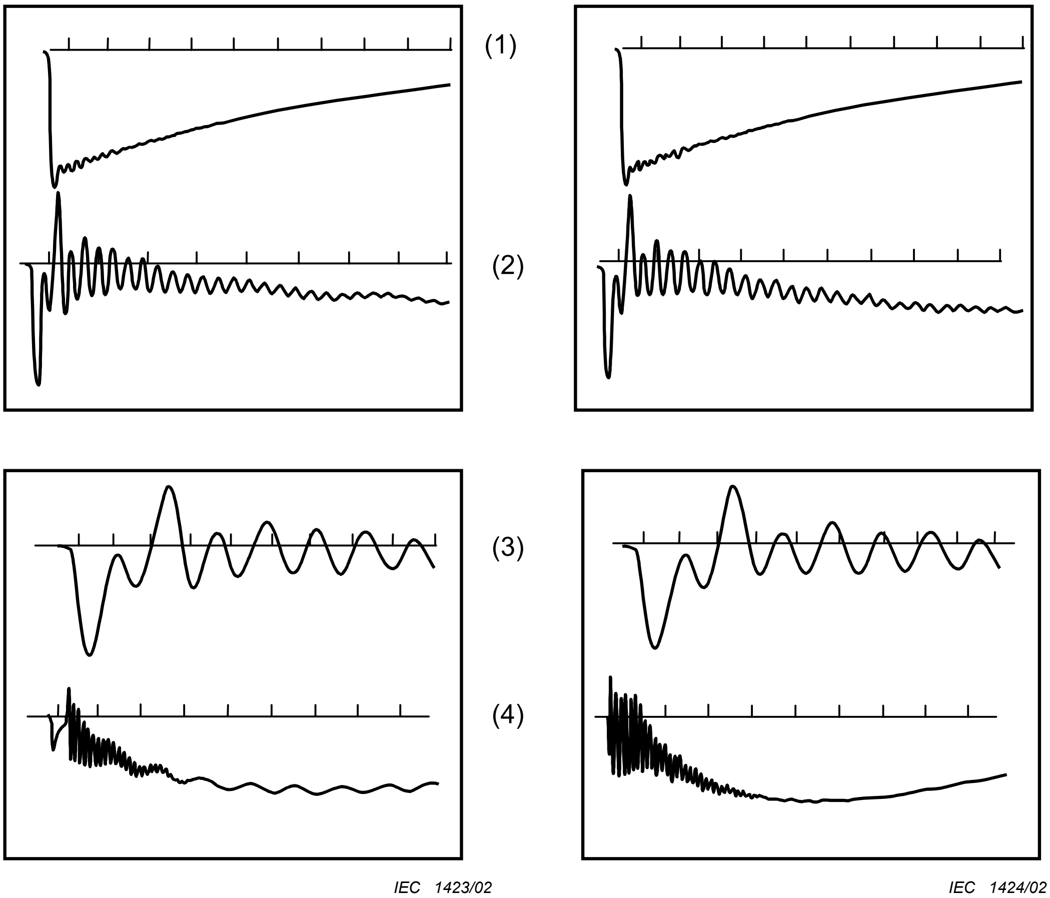


Figure B.4a – Full wave (100 %) without fault

Figure B.4b – Full wave (100 %) with fault

Key

1 applied impulse, 100 µs sweep

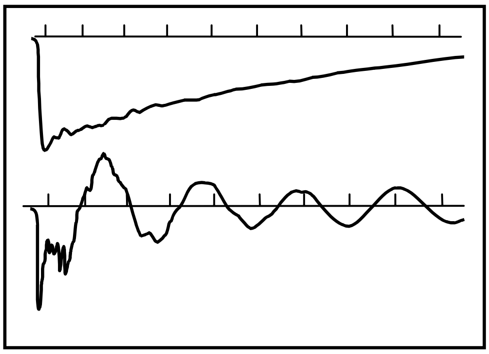
2 neutral current, 100 µs sweep

3 neutral current, 25 µs sweep

4 neutral current, 250 µs sweep

NOTE Failure indicated by minor variations on all records of second full-wave voltage application.

Figure B.4 – Lightning impulse, full-wave failure – Breakdown between leads of two 1,1 % sections of outside tapping winding of 400 kV generator transformer



(1)

(2)

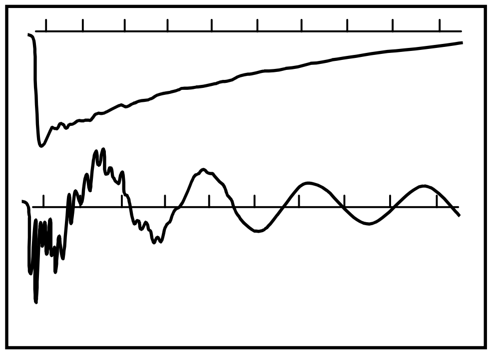


Figure B.5a – Reduced full wave (62,5 %) without fault

Figure B.5b – Full wave (100 %) with fault

Key

1 applied impulse, full wave, 100 µs sweep

2 capacitively transferred current from shorted adjacent winding to earth, 100 µs sweep

NOTE Failure indicated in both voltage and capacitively transferred current oscillograms.

Figure B.5 – Lightning impulse, full-wave failure – Breakdown short-circuiting one section of the fine-step tapping winding of a 220 kV transformer

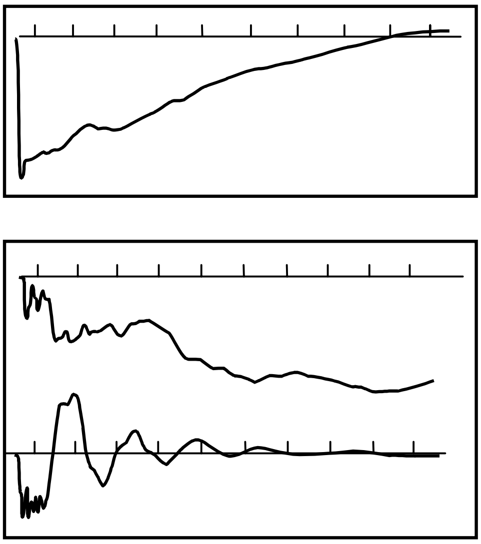


Figure B.6a – Reduced full wave (62,5 %) without fault

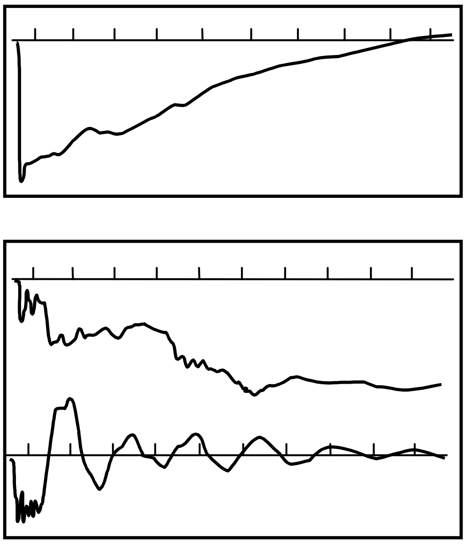


Figure B.6b – Full wave (100 %) with fault

Key

1 applied impulse, 100 µs sweep

2 neutral current, 100 µs sweep

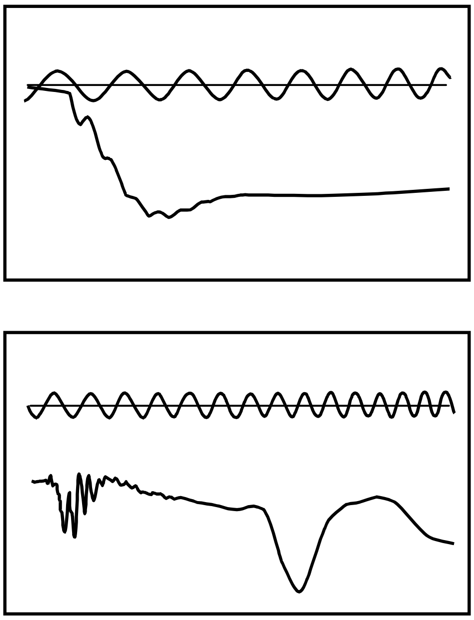
3 capacitively transferred current from shorted adjacent winding to earth, 100 µs sweep

NOTE Failure after 30 µs to 35 µs, clearly indicated in both neutral and capacitively transferred current oscillograms and no indication in the applied voltage oscillogram.

Figure B.6 – Lightning impulse, full-wave failure – Breakdown between parallel conductors of a main high-voltage winding of a 220/110 kV transformer

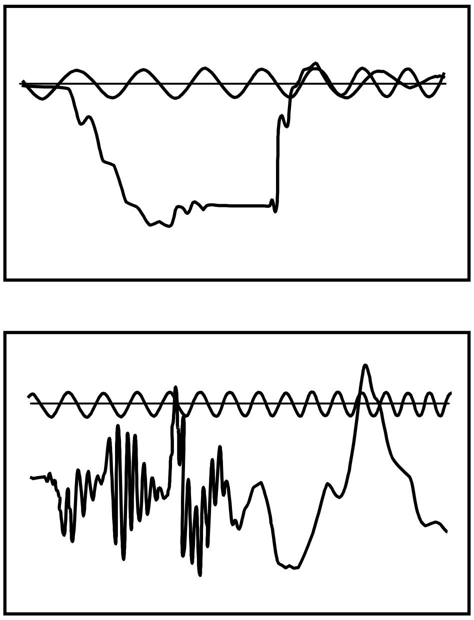
(1)

(2)



IEC 1429/02

Figure B.7a – Full wave (100 %) without fault



IEC 1430/02

Figure B.7b – Chopped wave (115 %) With fault (Note 1)

(Amplitudes not equalized)

Key

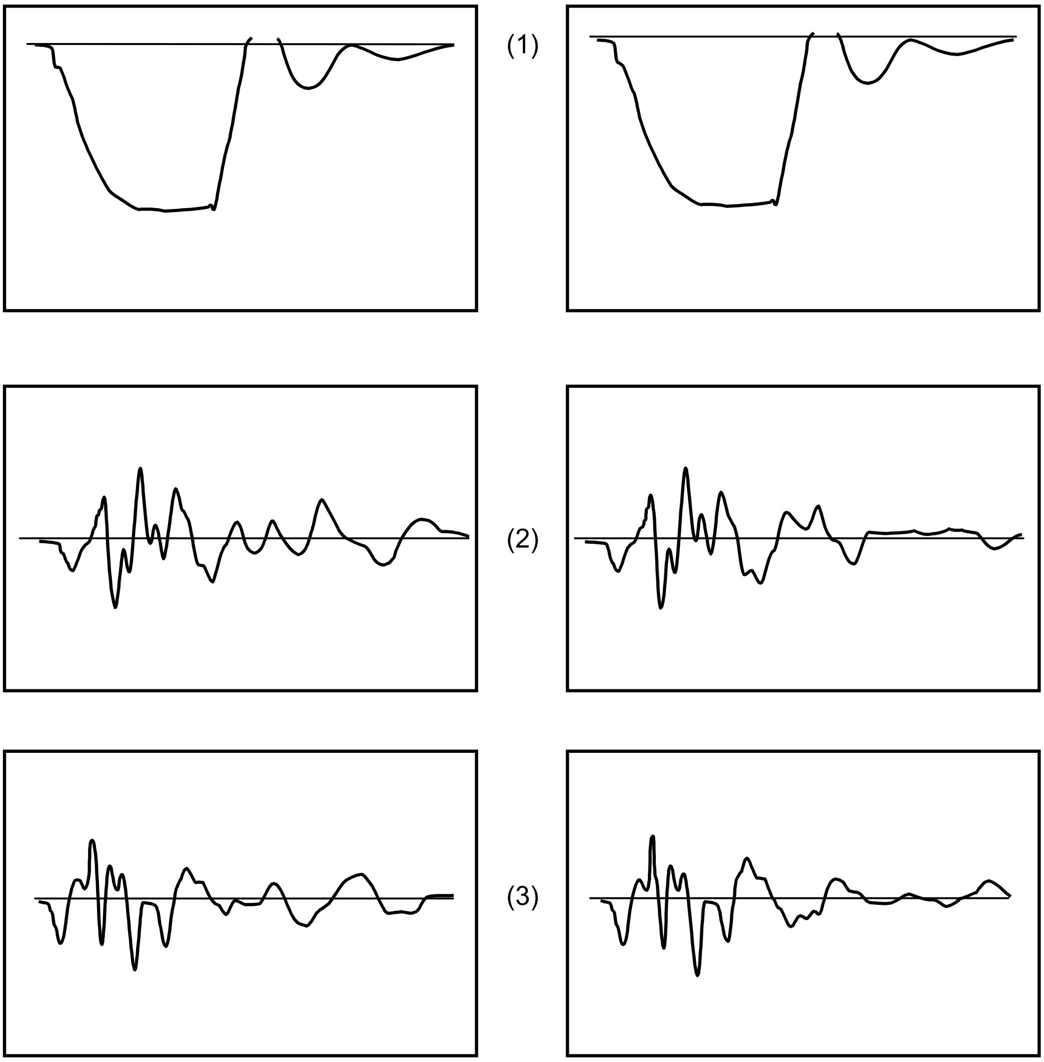
1 applied impulse, 10 μs sweep

2 neutral current, 15 μs sweep

NOTE 1 Since failure occurred before the instant of chopping it is therefore regarded as a full-wave failure.

NOTE 2 Failure just after the peak and before the instant of chop indicated by a 10 % drop in the voltage wave and by the neutral current oscillogram.

Figure B.7 – Lightning impulse, full-wave failure – Breakdown between foils of 66 kV bushing on tested winding



IEC 1431/02 IEC 1432/02

Figure B.8a – Reduced chopped wave (60 %) without fault

Figure B.8b – Chopped wave (100 %) with fault

Key

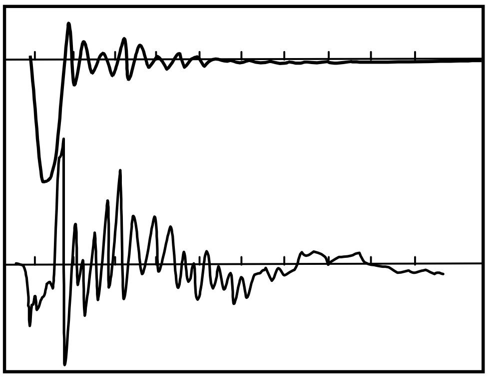
1 applied impulse, 10 µs sweep

2 capacitively transferred current from the shorted adjacent winding to earth, 50 µs sweep

3 neutral current, 50 µs sweep

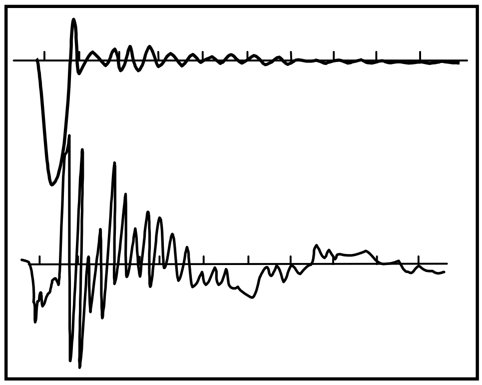
NOTE Failure after 10 µs to 15 µs clearly indicated in transferred current and neutral current oscillograms.

Figure B.8 – Lightning impulse, chopped-wave failure – Breakdown between turns in the main high-voltage winding of a 115 kV transformer



IEC 1433/02

Figure B.9a – Reduced chopped wave (70 %) without fault



IEC 1434/02

Figure B.9b – Chopped wave (115 %) with fault

Key

1 applied impulse, chopped wave, 50 µs sweep

2 capacitively transferred current from the shorted adjacent winding to earth, 50 µs sweep

NOTE Failure indicated immediately after chopping in both the voltage and capacitively transferred current oscillograms.

Figure B.9 – Lightning impulse, chopped-wave failure – Breakdown between turns in a fine-step tapping winding of a 220 kV transformer

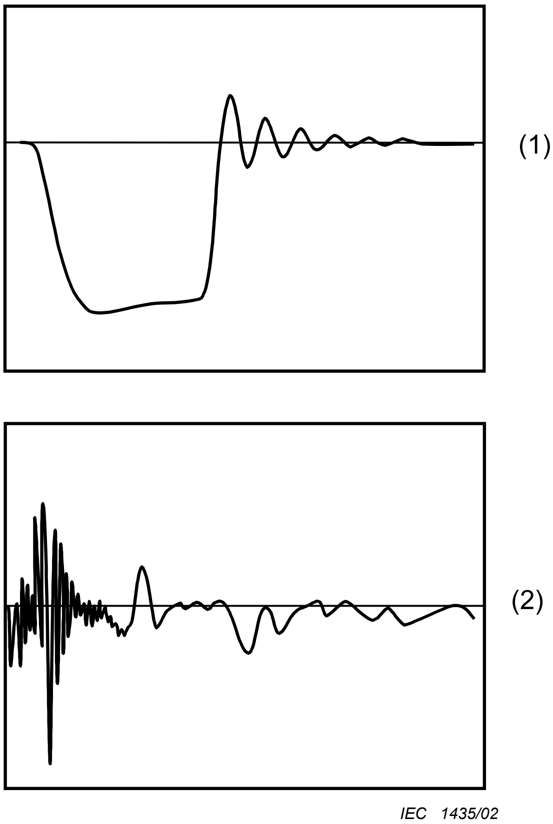


Figure B.10a – Reduced chopped wave (75 %)

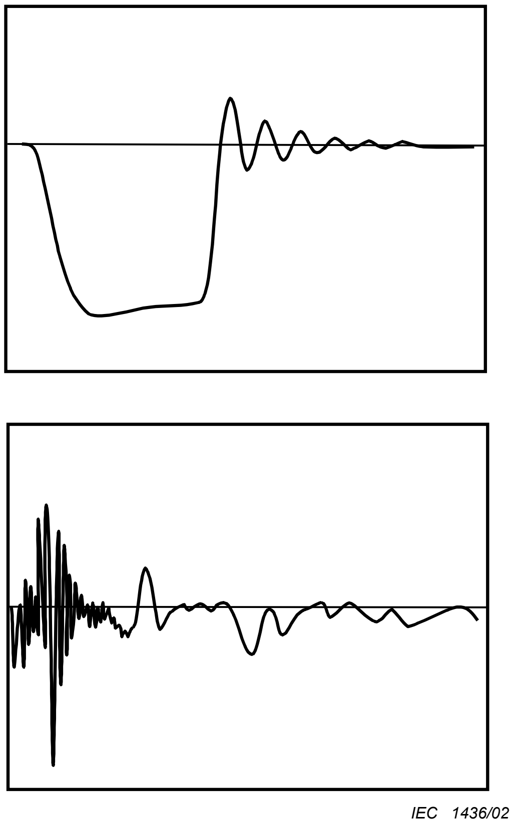


Figure B.10b – Chopped wave (100 %)

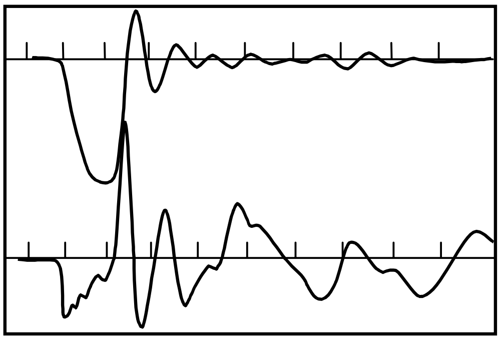
Key

1 applied impulse, 10 µs sweep

2 neutral current, 100 µs sweep

NOTE Identical voltage and neutral current records obtained when no difference in times to chopping.

Figure B.10 – Chopped lightning impulse – Impulses at different voltage levels with identical times to chopping when testing a 115 kV transformer



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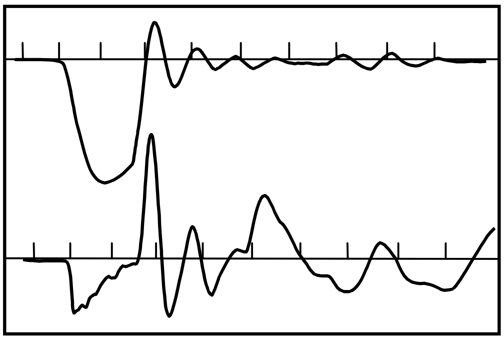


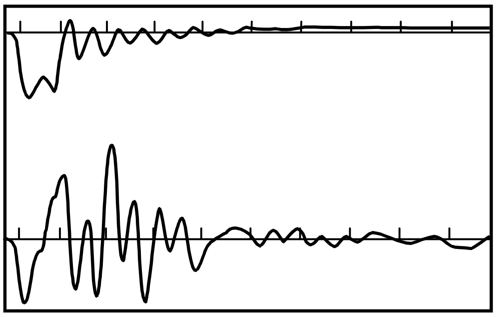
IEC 1437/02

IEC 1438/02

Figure B.11a – Reduced chopped wave (62,5 %)

Figure B.11b – Chopped wave (100 %)

NOTE Tests with large differences in times to chopping (high-voltage winding). Note changes in the superimposed high-frequency oscillations on the capacitively transferred current and changes in the voltage wave after chop.



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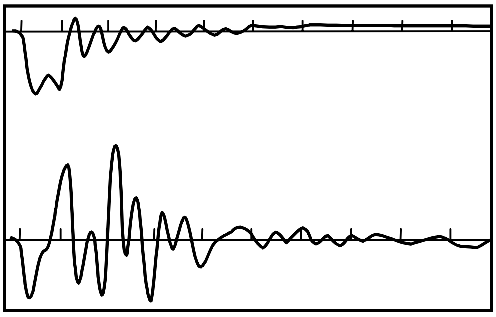


IEC 1439/02

IEC 1440/02

Figure B.11c – Reduced chopped wave (62,5 %)

Figure B.11d – Chopped wave (100 %)

NOTE Tests with small differences in times to chopping (low-voltage winding). Note changes in the superimposed high-frequency oscillations on the capacitively transferred current but virtually no difference in the voltage waves.

Key

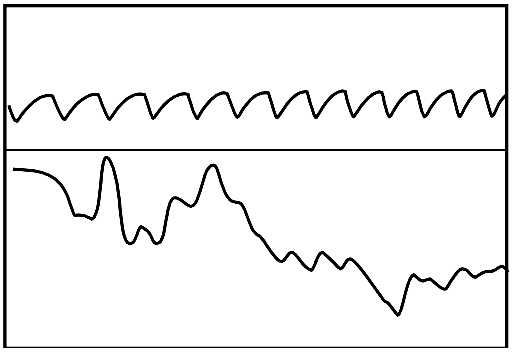
1 applied impulse, 25 µs sweep

2 capacitively transferred current, 25 µs sweep

3 applied impulse, 50 µs sweep

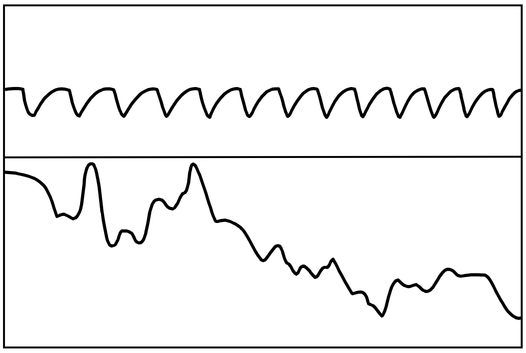
4 capacitively transferred current, 50 µs sweep

**Figure B.11 – Chopped lightning impulse –
Effects of differences in times to chopping when testing a 220 kV transformer**



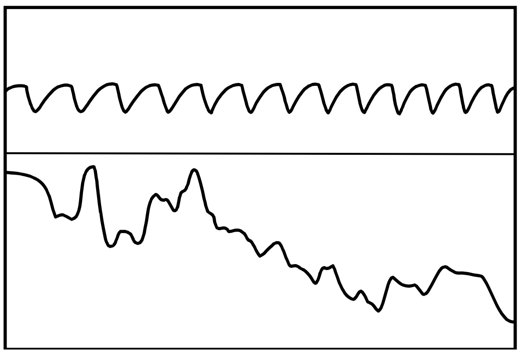
IEC 1441/02

Figure B.12a –Reduced full wave (50 %)



IEC 1442/02

Figure B.12b – Reduced full wave (75 %)



IEC 1443/02

Figure B.12c – Full wave (100 %)

NOTE 1 All three oscillograms show neutral current, 75 µs sweep.

NOTE 2 The changes in waveshape shown above are more marked than those which generally result from the presence of non-linear resistors.

**Figure B.12 – Full lightning impulse –
Effect of non-linear resistors embodied in neutral end on-load tap-changer
of a transformer with separate windings**

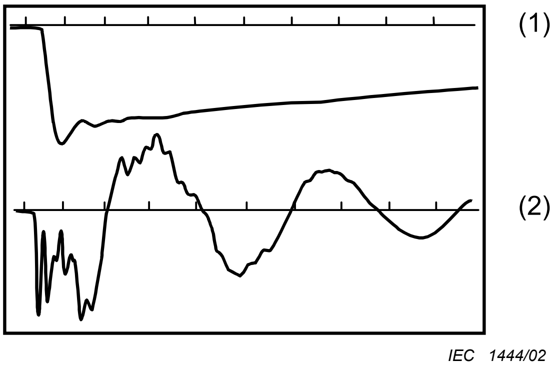
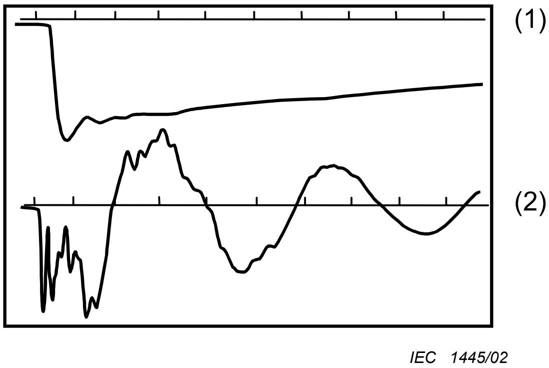


Figure B.13a – Reduced full wave (62,5 %)



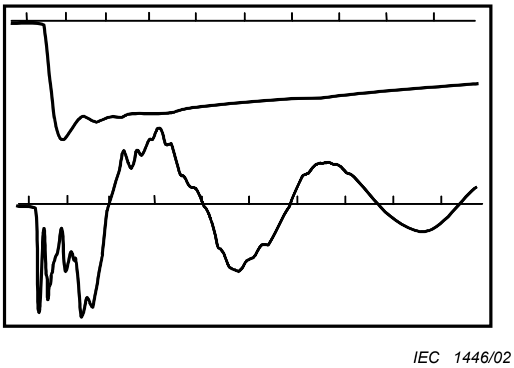


Figure B.13b – First full wave (100 %)

Figure B.13c – Second full wave (100 %)

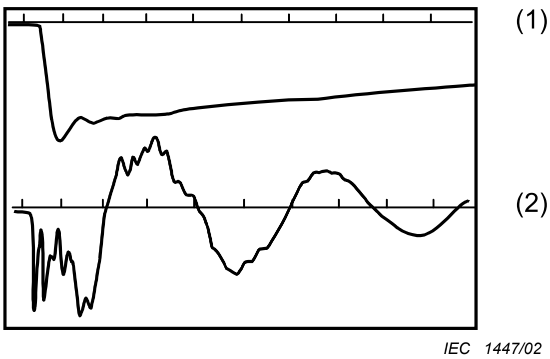


Figure B.13d – Final reduced full wave (62,5 %)

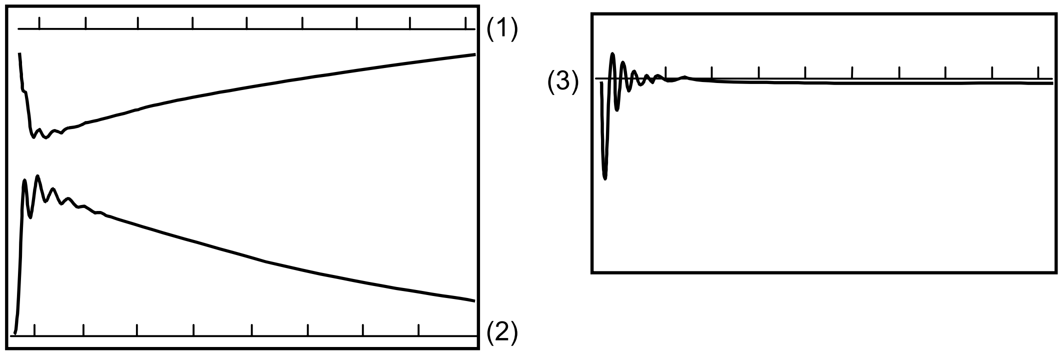
Key

1 applied impulse, 50 µs sweep

2 capacitively transferred current, 50 µs sweep

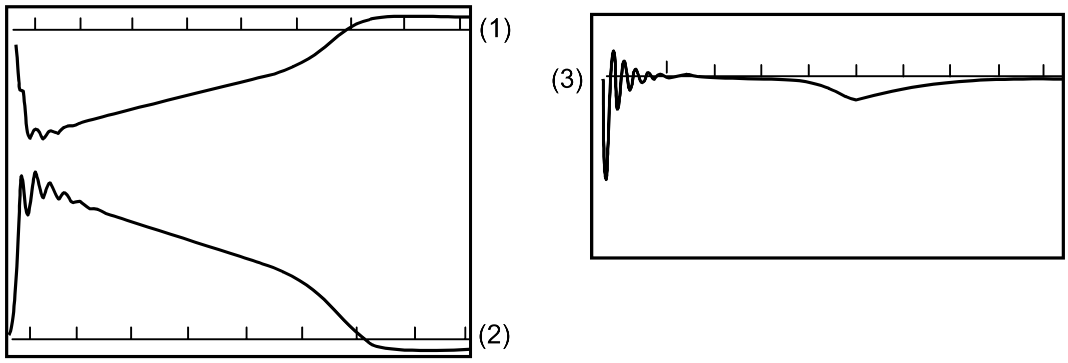
NOTE Comparison of the capacitively transferred current records for the 100 % voltage level with those for the 62,5 % voltage level shows initial high-frequency changes.

Figure B.13 – Full lightning impulse – Effect of generator firing differences at different voltage levels when testing a 400 kV transformer



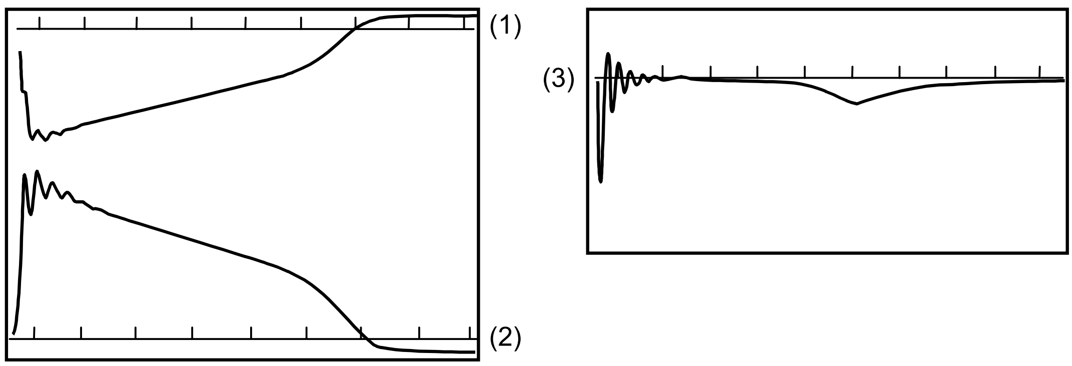
IEC 1448/02

Figure B.14a – 62,5 % test level



IEC 1449/02

Figure B.14b – First 100 % test level



IEC 1450/02

Figure B.14c –Second 100 % test level

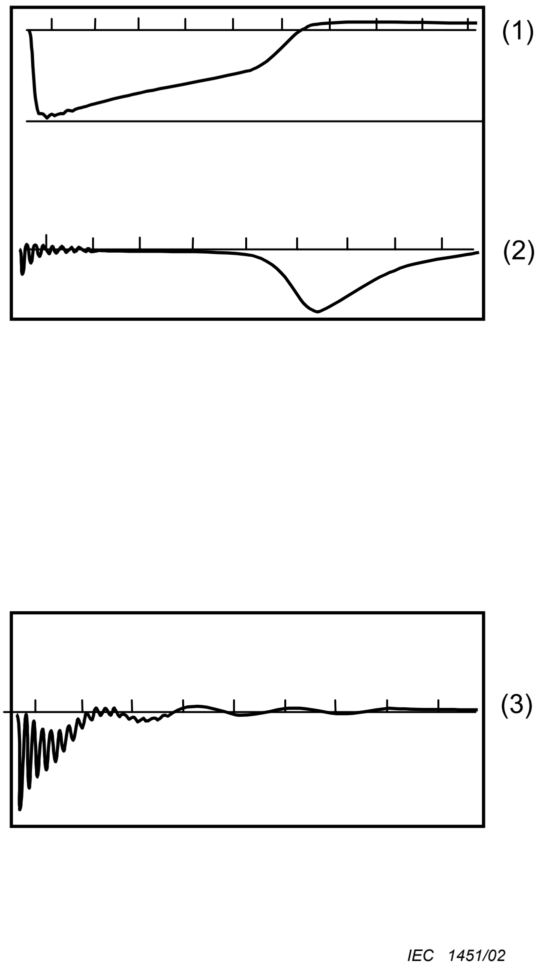
Key

1 applied switching impulse, 5 000 µs sweep

2 induced switching impulse voltage between the inter-connected terminals of the non-tested phase winding and earth (52 % of the applied voltage, positive polarity), 5 000 µs sweep

3 neutral current, 5 000 µs sweep

Figure B.14 – Switching impulse –
Satisfactory test on a 400 kV three-phase generator transformer



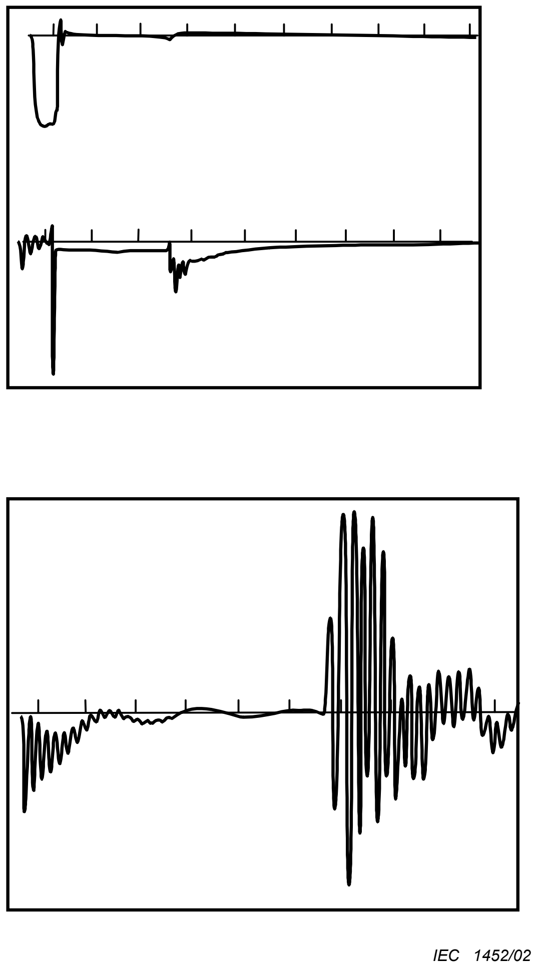


Figure B.15a – 90 % test level without fault

Figure B.15b – 100 % test level with fault

Key

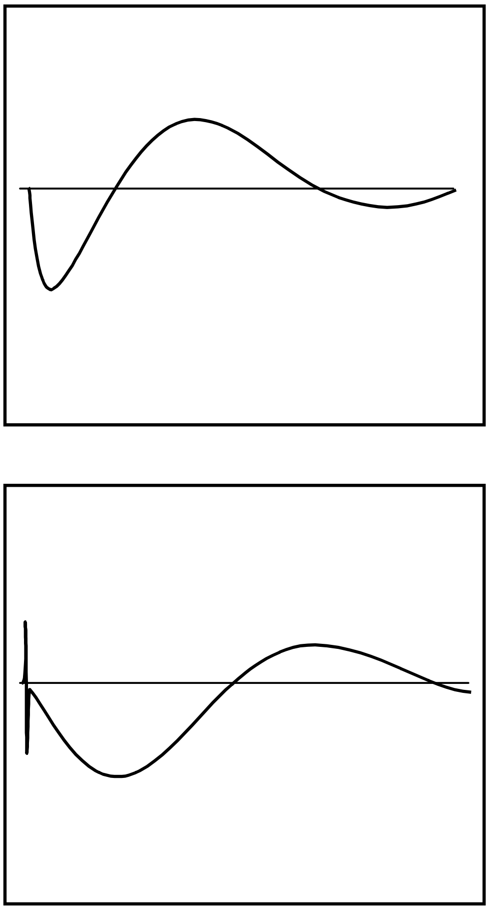
1 applied switching impulse, 5 000 µs sweep

2 neutral current, 5 000 µs sweep

3 neutral current, 500 µs sweep

NOTE Failure indicated at approximately 300 µs at 100 % test level.

Figure B.15 – Switching impulse – Breakdown by axial flashover of the main high-voltage winding of a 525 kV single-phase, generator transformer



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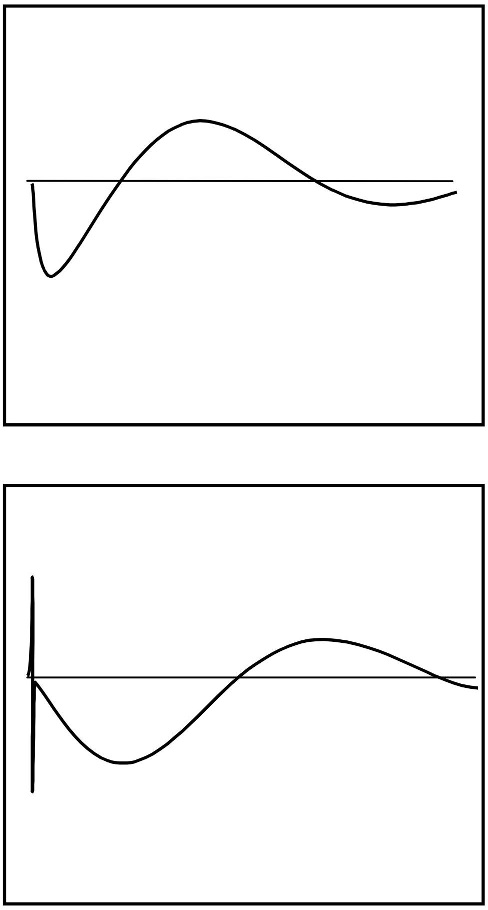


IEC 1453/02

IEC 1454/02

Figure B.16a – Reduced test level (60 %)

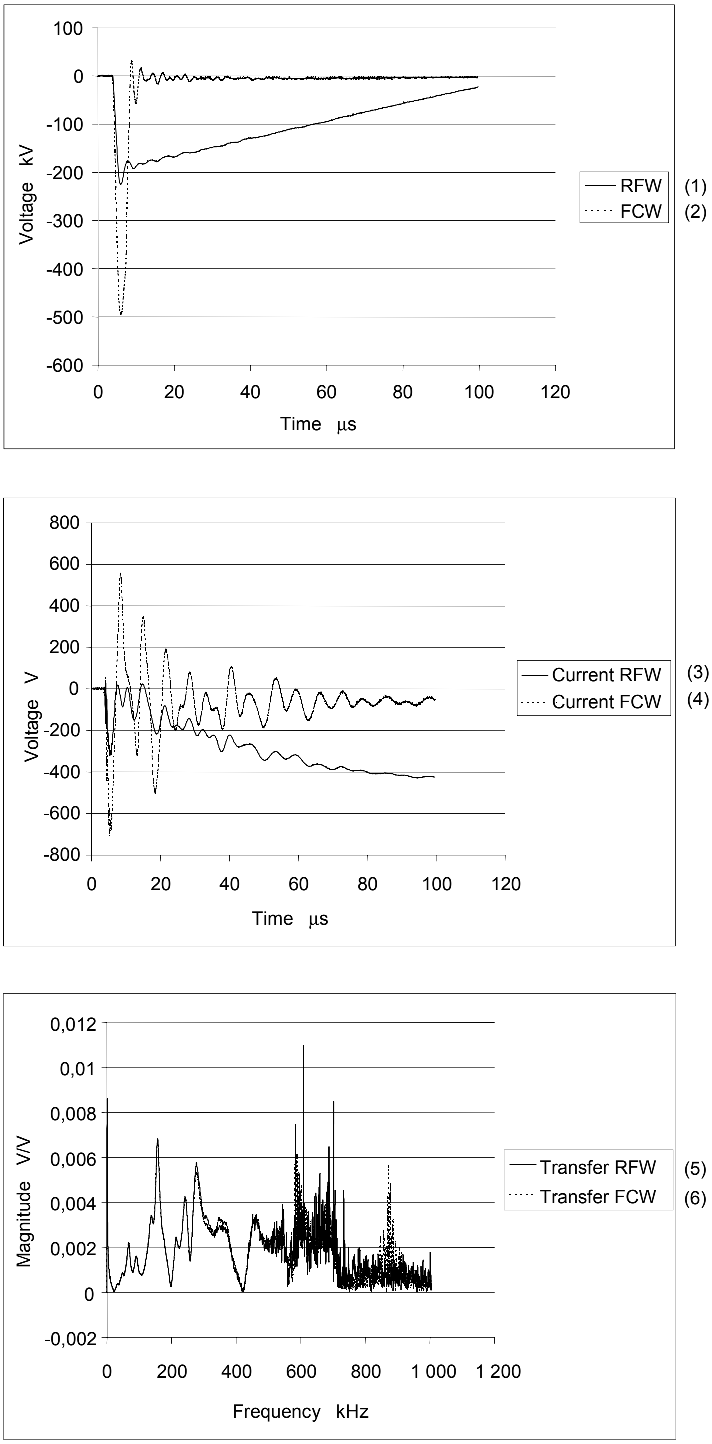
Figure B.16b – Test level (100 %)

Key

1 applied impulse, 5 000 µs sweep (T_1 200 µs, T_d 225 µs, T_z 1 000 µs)

2 neutral current, 5 000 µs sweep

**Figure B.16 – Switching impulse –
Satisfactory test on a 33 Mvar, 525 kV single-phase shunt reactor**



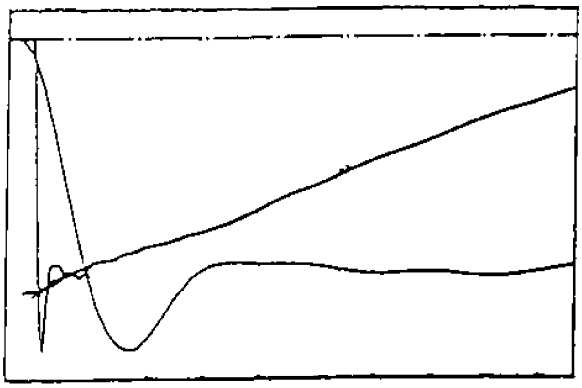
IEC 1455/02

NOTE Comparison of a reduced full lightning impulse wave (RFW) and a full chopped wave (FCW) on the same terminal of the same transformer. Because the chopped wave contains more high-frequency input for the admittance transfer function, deviations between the RFW and FCW transfer functions only occur at high frequencies.

Key

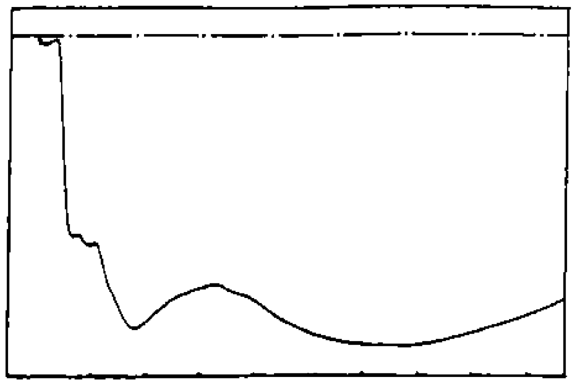
1 reduced full-wave RFW
2 full chopped-wave FCW
3 neutral current at RFW
4 neutral current at FCW
5 transfer (admittance) function at RFW
6 transfer (admittance) function at FCW

Figure B.17 – Lightning impulse – Comparison of the transfer function of a full wave and a chopped wave



IEC 1456/02

Figure 18a – Applied voltage

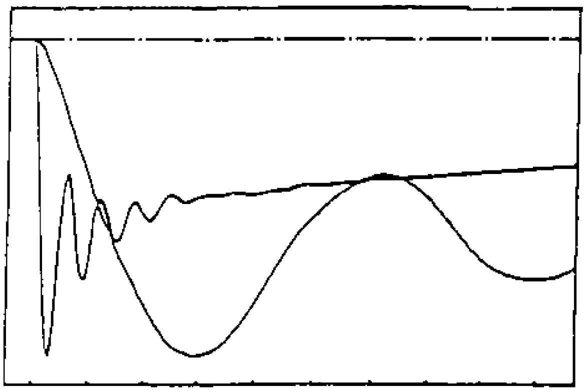


IEC 1457/02

Figure 18b – Neutral current

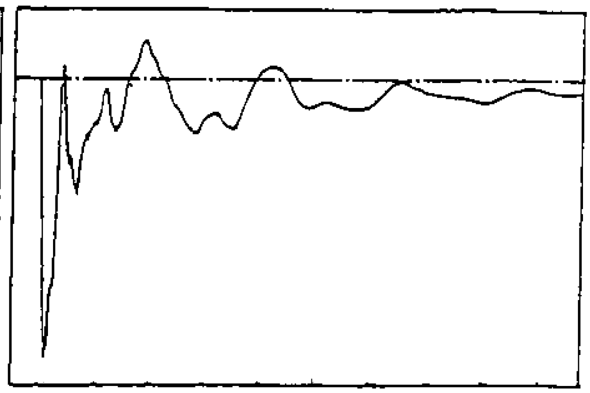
NOTE Wave with 19 % overshoot evaluated by tangent through tail decay according to IEC 60060-1, leading to an error of greater than 10 % in amplitude evaluation.

Figure B.18 – Full lightning impulse – Evaluation of a non-standard waveshape – Influence of in-built smoothing algorithms in digitizers



IEC 1458/02

Figure 19a – Applied voltage

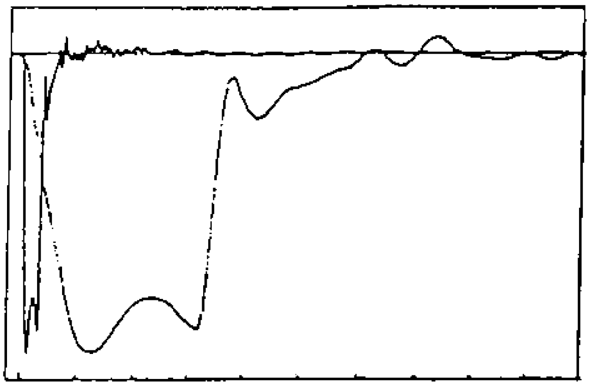


IEC 1459/02

Figure 19b – Neutral current

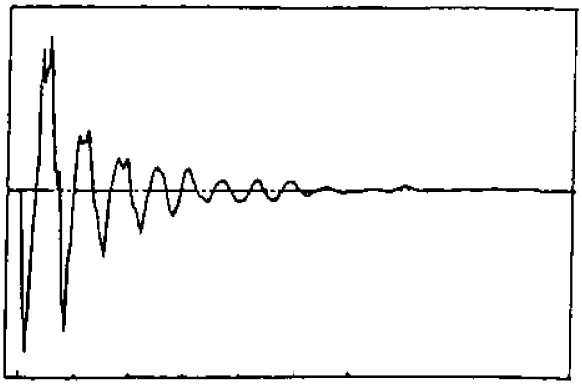
NOTE The digitizer evaluates the time to half-value as 5 µs based on the first passage of the super-imposed oscillations, whereas evaluation according to IEC 60060-1 shows 50 µs.

Figure B.19 – Full lightning impulse – Non-standard waveshape, superimposed oscillations with >50 % amplitude and frequency <0,5 MHz



IEC 1460/02

Figure 20a – Applied voltage

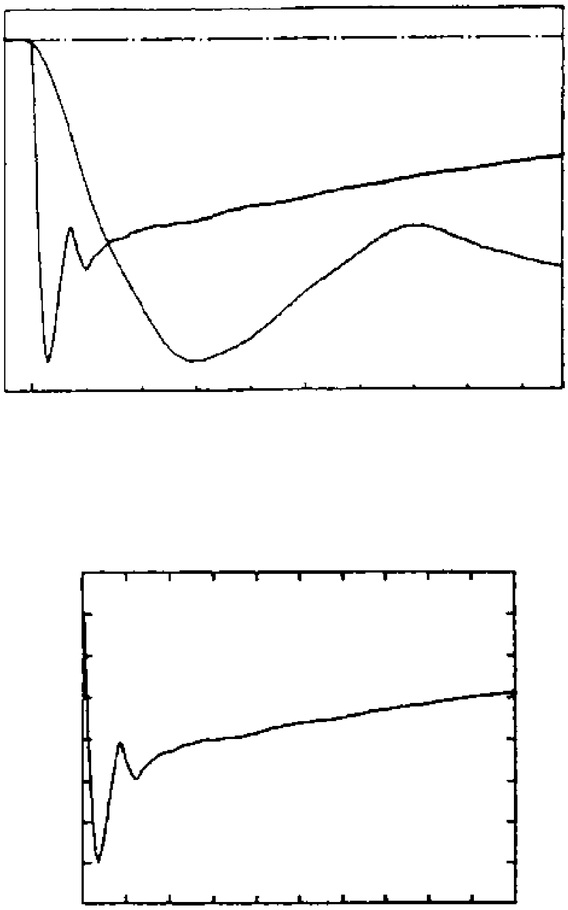


IEC 1461/02

Figure 20b – Neutral current

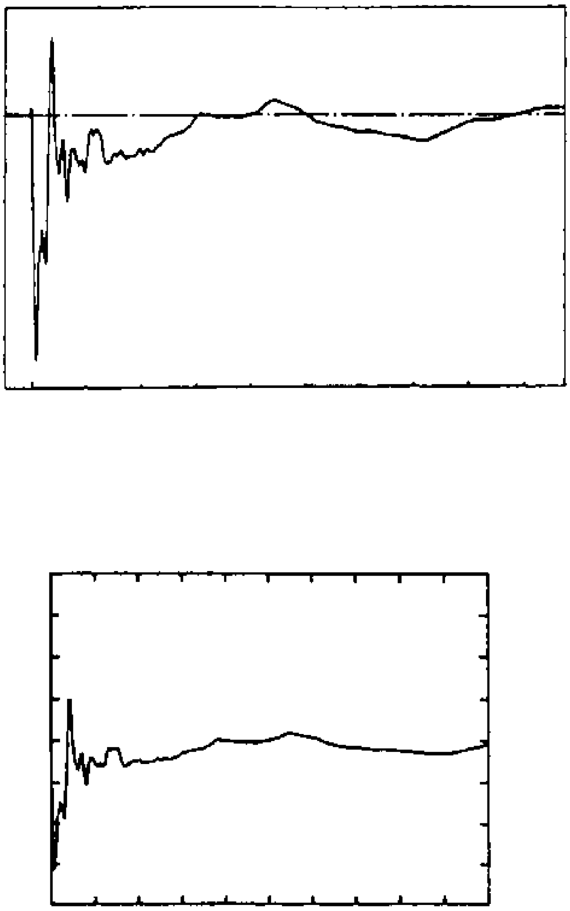
NOTE Non-standard chopped wave on a layer type winding. The layer impedance avoids rapid collapse and oscillations around zero of the chopped wave to earth.

**Figure B.20 – Chopped lightning impulse –
Non-standard chopped wave on a layer type winding**



IEC 1462/02

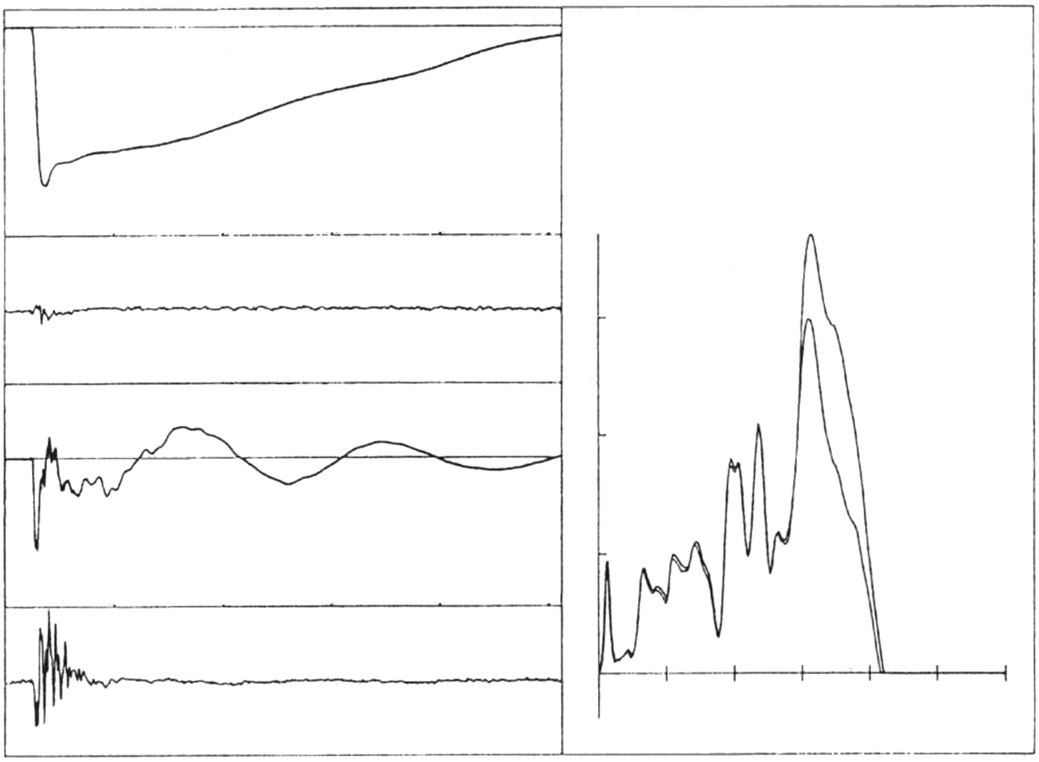
Figure 21a – Applied voltage



IEC 1463/02

Figure 21b – Neutral current

**Figure B.21 – Full lightning impulse –
Non-standard waveshape, comparison of non-standard waveshapes
by digitizers of different make from the same recording**



NOTE Measuring cable sparkover from LV winding to different earth than tank and generator earth. 400 MVA G.S.U. 220/21 kV at HV test.

Figure B.22a – No indication in voltage; clear indication in current; clear indication in transfer function

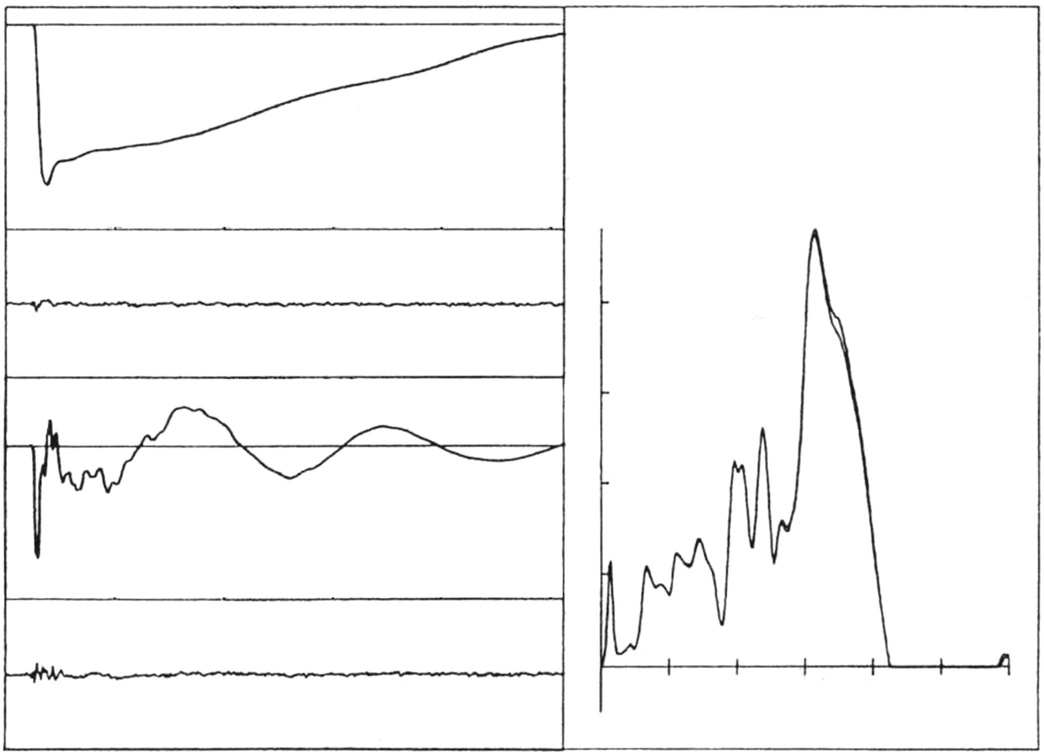


Figure B.22b – After correction perfect match of all real time and transfer function traces

Figure B.22 – Full lightning impulse – Test-circuit problem caused by a sparkover to earth from a measuring cable

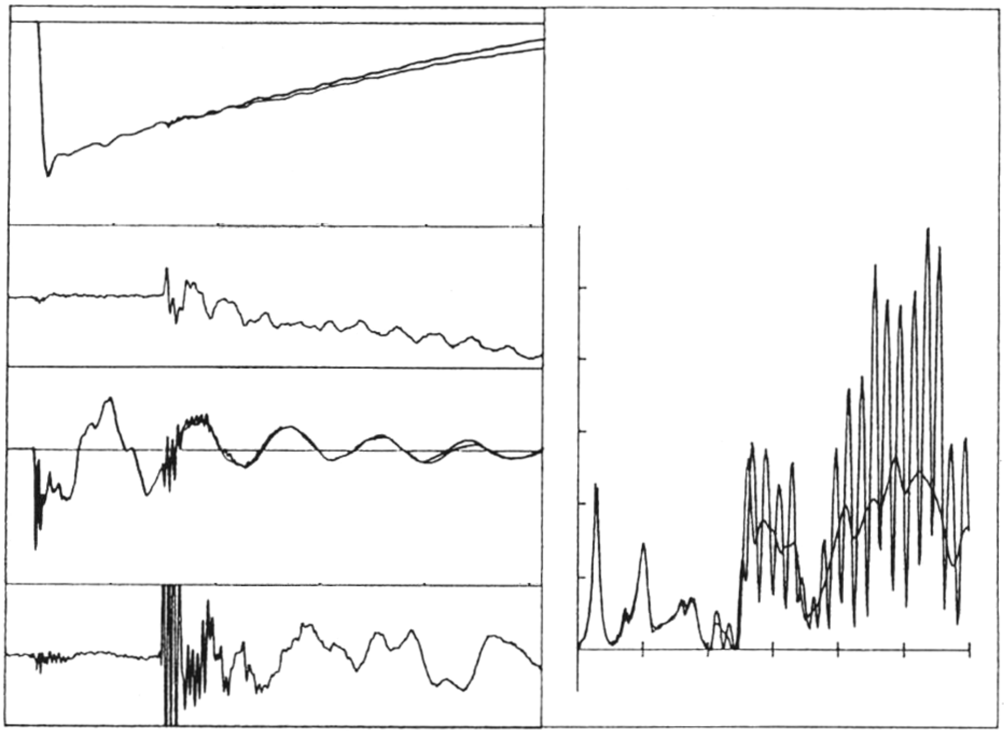


Figure 23a – Tap changer lead flashover between taps of a 300 MVA, 400/110/30 kV transformer

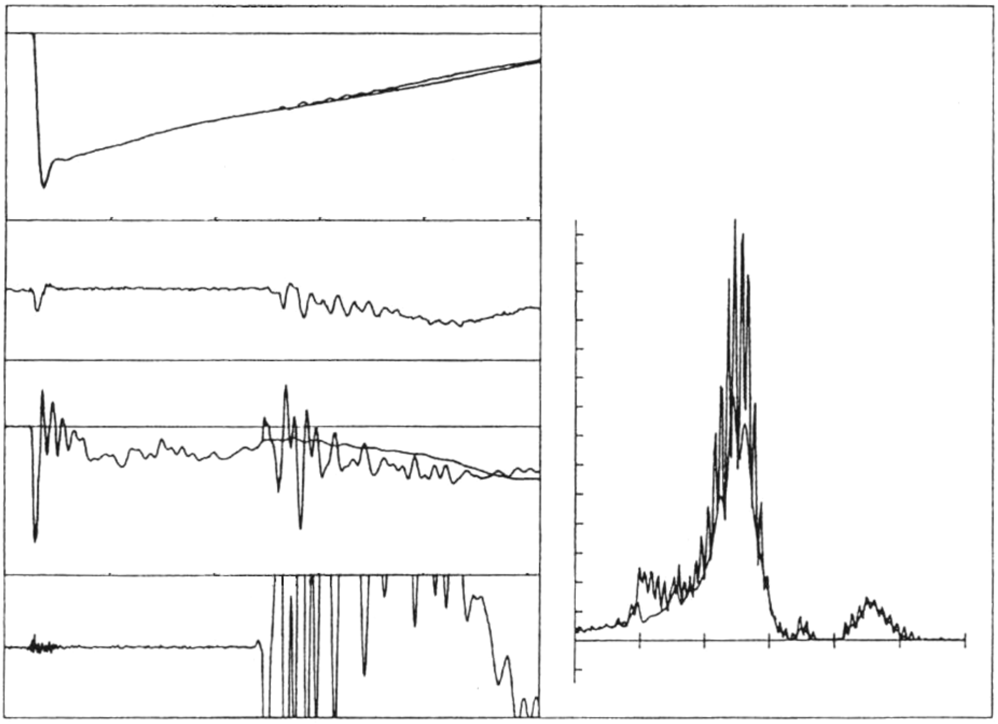


Figure 23b – Flashover between coarse and fine tapping windings

NOTE Significant changes in both real time response and in transfer function.

Figure B.23 – Full lightning impulse – Failure digital recordings of a flashover between tap leads of a tap changer and of a flashover between coarse and fine tapping windings

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